

1992

Interactive Graphics-Based Musculotendon Modeling for Reconstructive Surgery of the Hand.

Inmo Yoon

Louisiana State University and Agricultural & Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_disstheses

Recommended Citation

Yoon, Inmo, "Interactive Graphics-Based Musculotendon Modeling for Reconstructive Surgery of the Hand." (1992). *LSU Historical Dissertations and Theses*. 5366.

https://digitalcommons.lsu.edu/gradschool_disstheses/5366

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Historical Dissertations and Theses by an authorized administrator of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

U·M·I

University Microfilms International
A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
313/761-4700 800/521-0600

Order Number 9301114

**Interactive graphics-based musculotendon modeling for
reconstructive surgery of the hand**

Yoon, Inmo, Ph.D.

The Louisiana State University and Agricultural and Mechanical Col., 1992

U·M·I

**300 N. Zeeb Rd.
Ann Arbor, MI 48106**

INTERACTIVE GRAPHICS BASED MUSCULOTENDON MODELING FOR RECONSTRUCTIVE SURGERY OF THE HAND

A Dissertation

**Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy**

in

The Department of Mechanical Engineering

by

Inmo Yoon

B.S., HanYang University, Seoul, Korea, 1981

M.S.M.E., Louisiana State University, 1988

May 1992

Acknowledgements

The author wishes to express his sincere and deepest gratitude to his major professor, Dr. David E. Thompson, for his guidance and financial support during the preparation of this work. Meeting and working with him for the past several years has been a precious and enjoyable experience, and one which the author will not forget for the rest of his life. His personal and professional life style has been a model for the author throughout his academic career and will continue to be in his future endeavors.

The author also wishes to thank Dr's. George D. Catalano, Mehdy Sabaghian, and Warren N. Waggenspack Jr. for their services on his advisory committee. Special thanks also go to Dr. J. Bush Jones in the Computer Science Department for his service as a minor professor and Mr. Alaric Hagg at the Interactive Modeling Research Laboratory of LSU for his enormous help as the system manager.

Very deep thanks go to the researchers of the Paul W. Brand Rehabilitation Research Center at the National Hansen's Disease Center at Carville, Louisiana.

Dr. William L. Buford, currently at the University of Texas at Galvestone the School of Medicine, Dr. Loyd M. Myers, and Mr. David J. Giurintano whose friendship and help will always be remembered by the author.

The author would like to thank the surgeons who spent their own time and money evaluating this work. The author also wishes to express his immeasurable appreciation to his father, mother-in-law, brothers, and sisters for their love and encouragement.

Special thanks are due to the author's wife, Eunsun, and daughter, Suh Young, whose love and support made this work possible.

This work was funded in part by grant from Digital Equipment Corporation, Board of Regents (LEQSF(1987-90)-RD-B-9), and the Gillis W. Long National Hansen's Disease Center (HRSA-240-89-0006).

Table of Contents

Acknowledgements	ii
List of Figures	vi
Abstract	vii
1 Introduction	1
1.1 Objective of the Research	3
1.2 Research Environment	5
1.3 Nomenclature	7
2 Background	9
2.1 Muscle Force and Torque Analysis	9
2.2 Mathematical and Graphical Modeling	11
2.3 Moment Arm and Tendon Excursion	13
3 Interactive Graphical and Math Modeling of Muscle and Tendon	15
3.1 Data Structure	15
3.2 Interactive Graphical Modeling of the Hand	19
3.2.1 PHIGS	19
3.3 Math Modeling of Muscle and Tendon	28
4 Tendon Path Planning	44
4.1 An Example of Simulation	44
4.2 Results	54
5 Evaluation Program	60
6 Conclusions and Future Extensions	65
6.1 Conclusions	65
6.2 Future Extensions	69
Bibliography	72

Appendix A List of Questionnaire	75
Appendix B Summary of Review Statements	78
Vita	95

List of Figures

3.1	A Stardent GS1000 display of the hand	20
3.2	The hand with each joint rotated.	21
3.3	An example structure	23
3.4	The structure hierarchy of the hand used in this work.	24
3.5	Basic structure of the sarcomere and muscle fiber.	29
3.6	Mechanical representation of a musculotendon unit based on Hill's concept	31
3.7	Simplified mechanical representation of a musculotendon unit. . .	33
3.8	Normalized length-force diagram of a muscle fiber	35
3.9	Stress-strain diagram of a tendon	36
4.1	The coordinate system of the hand	45
4.2	The display of the hand in resting position	48
4.3	The hand that is rotated -90 degree about x axis and 90 degree about y axis.	49
4.4	Two orthogonal displays of the hand along with two orthogonal cursors.	50
4.5	The procedure of picking up the tendon path points.	51
4.6	The initial tendon path that is the path for the finger in resting position.	52
4.7	Several tendon paths as a result of joint rotation.	53
4.8	The excursion and moment arm for flexion of the FDP at the MP joint of the middle finger with the PIP and DIP joints in extension	56
4.9	The excursion and moment arm for flexion of the FDP at the PIP joint of the middle finger with the MP joint in extension	57
4.10	The excursion and moment arm for flexion of the FDP at the DIP joint of the index finger with the MP and PIP joints in extension.	58
4.11	The simulation result	59

Abstract

This research has been directed at studying and developing a prototype research and clinical Computer Aided Design (CAD) tool to be used for planning tendon paths in hand reconstructive surgery. Of equal importance is the goal of having an educational tool for teaching hand biomechanics to students of this specialty. The application of CAD to rehabilitative surgery of the hand is a new field of endeavor. There are currently no existing commercial products designed to assist the orthopedic surgeon in planning these complex procedures. Additionally, orthopedic surgeons are not trained in mechanics, kinematics, math modeling, or the use of computers. It was also our intent to study the mechanisms and the efficacy of the application of CAD techniques to tendon transfer surgery.

Through this research the following advances have been made:

- creation of interactive 3D tendon path definition tools.
- creation of software to calculate tendon excursion from an arbitrary tendon path crossing any number of joints.

- creation of a model to interactively compute and display the forces in muscle and tendon.
- creation of an environment to help surgeons evaluate the consequences of a simulated tendon transfer operation when a tendon is lengthened, rerouted, or reattached in a new location.

It also has been one of the primary concerns in this research that an interactive graphical surgical workstation must present a natural, user-friendly environment to the orthopedic surgeon user. Additionally, this workstation must ultimately aid the surgeon in helping his patient or in doing his work more efficiently or more reliably. This work therefore includes a study of the usefulness of such a workstation as perceived by the orthopedic surgery community.

Chapter 1

Introduction

A tendon is an integral part of muscle. It is, however, considered to be fibrous connective tissue because it consists of collagenous tissue that attaches muscle to other structures such as bone. Thus, one end of the tendon is always attached to muscle and at the other end, the tendon fibers blend with the fibrous connective tissue of the structure to which they insert[24]. The tendon transmits a force to the structure that is generated by the muscle which in turn has been activated by the central nervous system (CNS). Patients with nerve damage due to a disease such as Hansen's Disease or an accident in daily life suffer from the lack of muscle force and the moments produced about joints.

Such a patient may regain the most elementary basic functions of the musculotendon through a tendon transfer operation. From time to time, however, the patient may become an unfortunate victim of an unsuccessful tendon transfer operation which could have been prevented if a surgeon had correctly predicted the outcome of the operation. The misjudgement of the surgeon about the op-

erations outcome could easily be the result of a lack of understanding of the basic concepts of biomechanics and kinematics of the hand. This knowledge is certainly not a normal component of the academic training of surgeons.

It is true that, until now, most of the tendon transfer operations are performed by surgeons on the basis of experience and intuition gained through years of practice. With the help of an interactive graphical system programmed with the laws of mechanics, these surgeons may simulate surgery on a computer model of specific patients and plan and evaluate the best operation for their patients' hands.

The application of an interactive computer graphical simulation to engineering and science has been implemented by many researchers in these fields. However, there has been no such attempt until the mid 1980's when Buford[14] developed a real-time interactive graphical simulation of the mechanics of the human thumb. With 3D realism, real-time dynamics and ease of human-computer interaction, this type of computer simulation brings the power of mathematical and graphical hand biomechanics modeling into the clinical realm.

The hand biomechanics workstation requires a graphical display which can give a realistic view of the movement of the hand. However, since the geometry of the musculoskeletal system of the hand is complicated, a two dimensional representation of the musculoskeletal structure is not considered to be an appropriate visualization technique. A 3D dynamic display of the system is essential

to accurately compute the length of the tendon path and the moment arm of the joint from which one can calculate the forces and torques in the hand.

This workstation can also have potential in the domain of patient education since it is possible to be able to demonstrate to them precisely what is planned when a surgical procedure is about to be carried out. Most of surgeons spend time with patients making drawings and trying to explain the details of the surgical procedure that have to be done and the basis of the procedure.

Conventional thought usually associates surgeons with the world of scalpels and sutures, not computers. However, as computers become convenient and powerful tools in every aspect of life, advancements in medical technology may hardly be imagined independent of the computer technology. Nevertheless, such computer tools are still not available in some medical applications such as prosthetics and orthopedic surgery. Thus, an interactive computer modeling system which can be used with little technical knowledge about computers is essential.

1.1 Objective of the Research

Louisiana State University has led in the development of a hand biomechanics workstation over the past 17 years. This 17 year effort has assumed that such a workstation would be both appropriate and useful to the orthopedic surgical community.

The objective of this research is to develop concepts and mathematical models of the human hand and to determine their relative usefulness and applicability

in a biomechanics workstation. Prior to testing the above *hypothesis*, additional advances in the state of knowledge were necessary to present a minimal software test suite. These advances were:

1. the development of a kinematic, hierarchical data structure, and display interface to provide interactive control of each joint axis.
2. the extension of the design of an arbitrary 3D tendon path using CAD techniques.
3. the linking of this path to the kinematic structure permitting evaluation of
 - moment arms,
 - tendon excursion, and
 - joint forces and torques.
4. The development of an *interactive* muscle model based on physiological behavior of skeletal muscle and mechanical properties of tendons.

The *validity* of the hand biomechanics workstation concept was then tested along with the models which comprise the workstation by having eight orthopedic surgeons use the workstation in a test program and then answering a formal questionnaire (Appendix A). For reference, the summary of their responses to the questionnaire are included in Appendix B.

1.2 Research Environment

There was an increasing demand for the interactive graphical workstation for tendon transfer surgery using a CAD approach. It was not possible, however, until Evans & Sutherland's PS series of graphics processors became available in the early 1980s. These systems cannot be used independently but must communicate with host computers for numerical processing[1]. The display and manipulation of objects can easily be controlled by Graphics Support Routines (GSR), a proprietary graphics library of E&S. In the joint LSU/GWLNHDC (G.W. Long National Hansen's Disease Center) laboratory, a VAX 11/750 was used as the host processor. This was found to be the limiting factor in the hand simulations.

Stardent Computer, a 3D workstation vendor that resulted from the merger of Stellar Computer and Ardent Computer Systems, has introduced a new computer, the Stardent Graphics Supercomputer GS1000 (Stellar), capable of high level of 3D vector generating performance and super computing that were the main reasons for being used in this work. It can transform and display 600,000 3D short vectors per second. Compared with the E&S PS300 that is capable of 45,000 vectors per second[1], it has an outstanding vector generating performance. The system provides powerful integer and floating point performance, 20-25 MIPS and 40 MFLOPS respectively.

The operating system of the Stardent is Stellix which is based on Release 3.0 of AT&T UNIX System V. The graphical user interface incorporates the

two important standards, the Application Visualization System Library User Interface (AVS LUI) and the Programmer's Hierarchical Interactive Graphics System (PHIGS) which will be more discussed in chapter 3. AVS LUI is a toolkit of X-Window system developed by the Stardent Computer Inc.. Both the PHIGS and X-Window software systems were chosen so that this work would be based on existing software standards, rather than on machine dependent softwares. All mathematical and graphical modeling computations were performed on a 3D high performance workstation, Stardent's Graphics Supercomputer Model GS1000. The X Window System is a portable software standard developed at the Massachusetts Institute of Technology's Project Athena. It controls the displays of engineering workstations and provides a standard environment to application software[26].

The system (GS1000) includes several high performance processors such as the multi-stream processor (MSP), the vector/floating point processor (VFP), the rendering processor (RP), and the input/output processor (IOP). MSP executes four instruction streams simultaneously. VFP contains four high-speed floating point compute engines, configured to work separately or in tandem. RP performs special graphics computations such as depth-cueing and shading. It can also transform and render 150,000 Gouraud-shaded triangular tiles per second. IOP handles communication with external busses, controllers, and peripheral devices.

1.3 Nomenclature

This section includes the definition of terms that are frequently used in this dissertation.

- Tendon path points - Points that a tendon passes through. These points defines a tendon path.
- Polyline - A set of two or three-dimensional connected lines.
- Structure element - The smallest piece in a structure that represents output primitives, attributes, transformations, labels, or structure invocations.
- Structure - A collection of elements.
- Traversal - Operation that processes a structure hierarchy for display. In order for a structure to be traversed the structure must be posted to a particular workstation, that is, traversal begins by posting the structure.
- Pennation angle - Angle between muscle fiber and tendon.
- Tendon Excursion - Change in length of tendon in the particular position relative to the reference position.
- Isometric contraction of muscle - Contraction of muscle producing a force but whose motion is prevented.
- Sarcomere - The contractile element of myofibrils.

- **Joint axis** - The center of rotation of the joint.
- **Fusiform muscle** - Spindle shaped muscle.
- **Pennated muscle** - Muscle that looks like a feather.

Chapter 2

Background

2.1 Muscle Force and Torque Analysis

Analytic calculation of forces and torques in the joints and muscles of the musculoskeletal system has been one of the challenging topics in the field of biomechanics.

Berme[9] investigated the total force exerted at each joint of the thumb and finger. He found that the external force measurements indicated that the force exerted by the thumb was about four times that exerted by the index finger.

Baildon *et al.*[8] proposed a different approach to modeling of human muscular activity. Their model has several advantages; it is relatively simple so that it needs less computation processing time and the iterative routine used in this model does not cause a significant error. The efficiency and accuracy of the model allow the analysis of a variety of aspects of human muscle behavior.

An *et al.*[4] developed an analytical model for human hand force analysis through anatomical study and measurement of multiple cadaveric specimens.

This model may have a potential application to determine forces under simulated abnormal conditions.

To simplify the geometrical forms of articular surfaces, Landsmeer[28] proposed three types of tendons crossing the joints. In his paper the first type was for a tendon running over a trochlea, which is appropriate for explaining tendon excursions of extensors and some flexors in the finger[12]. The second type was for a tendon traveling through a loop. The last type was for a tendon running through a tendon sheath.

Cooney *et al.*[17] analyzed internal forces in the thumb joints during pinch and grasp. To express the thumb structure in mechanical term, they assigned a mechanical equivalent to each joint, that is, a hinge joint to the interphalangeal joint that has one degree of freedom and a universal joint to metacarpophalangeal and carpometacarpal joints that have two degrees of freedom.

An *et al.*[6] developed a mathematical model to calculate internal forces in extensor and flexor pollicis longus of the thumb. The relationship between muscle force and integrated eletromyograms was obtained in terms of polynomial function.

Giurintano *et al.*[21] created a five link manipulator model for thumb motion using non-orthogonal non-intersecting axes of motion. Their model predicted different muscle-tendon unit forces, joint constraint forces and moments than Cooney's model[17].

Chao *et al.*[16] set up basic coordinate systems to define tendon locations and joint constraint forces and used Eulerian angles to define the orientation of finger digits in specific isometric hand functions. A combination method was used to resolve a system of 19 simultaneous equations (18 force and moment equilibrium equations and 1 constraint equation) with 23 unknowns. This study presented the minimal load requirements in finger joint prosthetic design.

2.2 Mathematical and Graphical Modeling

Buford[14,15] developed a 3D data structure which was acquired by taking eighteen radiographs at 10 degree increments, with the thumb fixture placed on the X-ray plate using B-splines to remove noise in the data. With this data structure he developed a real-time interactive graphics simulation of the mechanics of the human thumb using the Evans & Sutherland PS330.

Myers *et al.*[29] developed a system for the display, editing, and segmentation of anatomical data obtained from computerized tomography (CT) scans. This system can provide the interactive creation of a first approximation of an anatomically accurate set of individually addressable hand bones.

Thompson and Giurintano[35,22] presented a kinematic model of the flexor tendons of the hand. In their paper the tendons modeled were the flexor pollicis longus (FPL), the flexor digitorum profundus (FDP), and the flexor digitorum superficialis (FDS). The simulated tendons were displayed on an Evans and Sutherland PS330 color graphics terminal. The simulated maximum excursion compared favorably with the experimental data[5].

Delp *et al.*[19] studied the orthopedic surgical procedures of the lower extremity using interactive computer graphics. This modeling allows the user to visualize the musculoskeletal geometry and to manipulate the model parameters to study the biomechanical consequences. In acquiring the bone surface data, they used a three dimensional digitizer after marking the bone surfaces with a mesh of polygons.

Hoy *et al.*[25] developed a musculoskeletal model of the lower extremity for simulation studies of musculotendon function and muscle coordination during movement. This study is considered to be a theoretical and experimental background of the work by Delp[19]. They found that tendon slack length, optimal muscle-fiber length, and moment arm were different for each actuator, thus each actuator developed its peak isometric moment at a different joint angle.

Zajac[38] presented a comprehensive report about the modeling of the static and dynamic properties of tendon and muscle to formulate a generic, dimensionless model of the musculotendon actuator of the muscle and tendon for computer simulation. He also studied how the contractibility of the muscle and the elasticity of the tendon interact to specify the contraction process of the actuator.

Yoon *et al.*[37,36] developed a pseudo 3D tendon path planning method using an interactive graphical workstation. Their model was based on the assumption that the path was planar because most normal tendons do not have large out-of-plane paths.

Hatze[23] presented the dynamical behavior of a musculo-skeletal link system which consisted of the right thigh and the right lower leg. He stated that his model of skeletal muscle could be used for an energy optimization with a slight modification.

2.3 Moment Arm and Tendon Excursion

Ou[31] described the biomechanics of the carpometacarpal joint of the thumb by modeling joint kinematic behavior. A surgical Kirschner wire was used to keep the thumb immobilized through the interphalangeal and metacarpophalangeal joint and to allow the phalanges to be considered as a rigid and straight rod.

Buchner *et al.*[13] defined the tendon excursion equation of the finger on the basis of Landsmeer's models[28]. The authors also investigated the joint angle and the internal force of the finger using optimization methods.

Brand[10] stated that the moment arm of the tendon in relation to the given joint axis was proportional to the excursion and might be used to calculate the effectiveness of the proposed transfer and to analyze other effects that may be produced at other axes of joint motion. He also attempted to clarify the biomechanics of joints, employing simple concepts of the dynamics of fingers.

An *et al.*[7] compared available experimental techniques to determine orientations and moment arms of muscles and tendon excursions. They concluded that

various methods should be used as a cross check because each of the techniques had merit as well as disadvantages.

Doyle *et al.*[20] studied the pulley system of the flexor tendon of the thumb. They identified two annular pulleys and one oblique pulley in the thumb and stated that the oblique pulley in the proximal phalanx is the most important for maintenance of flexor pollicis longus action.

Chapter 3

Interactive Graphical and Math Modeling of Muscle and Tendon

3.1 Data Structure

The growth and development of images for medical use has been rapid with the advent of noninvasive imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), and ultrasound. The majority of three dimensional reconstructions of the human anatomy are based on CT scan and MRI image data.

A CT scan is an X-ray image of the body generated by computerized reconstructions. Each CT image is composed of many rows and columns of small, rectangular bricks called *volume elements* or *voxels*, for short. CT scans, which are based on the relative x-ray absorption of tissues, provides more information about the hard, dense structure of the skeletal system. Soft tissue information, however, is limited. MRI imaging, based on the emission of H_2 -atoms in alternating magnetic fields, provides much more information about soft tissues[34].

The geometric data upon which this dissertation is based consists of 172 nonoverlapping slices with 512×512 voxel resolution at 1 mm spacing by using a Siemens Somatom DR3 CT scanner. A compression algorithm was applied to the data to save storage space and improve the execution speed of the editor software [29]. The procedure for obtaining data requires the following six steps[34].

- (1) A set of serial CT or MR scans is obtained.
- (2) The entire bone structure is identified as an entity.
- (3) The structure is segmented into individual bones using a 3D graphic editor[29].
- (4) The segmented individual bones are hierarchically redefined using PHIGS's *structure* concept.
- (5) Joint axes of motion are interactively defined.
- (6) Transformation matrices are applied to reconstruct the kinematic hand model.

The transformation matrices used in the work for the kinematic hand model are as follows:

$$\begin{aligned}
 \| P_c \| &= \| P_c \| \\
 \| P_t \| &= [T(x_{11}, y_{11}, z_{11})] [R(x_{12})] [R(y_{12})] [R(z_{12})] [T(-x_{11}, -y_{11}, -z_{11})] \\
 &\quad \| P_{tmc} \| [T(x_{13}, y_{13}, z_{13})] [R(x_{14})] [R(y_{14})] [T(-x_{13}, -y_{13}, -z_{13})] \\
 &\quad \| P_{tpp} \| [T(x_{15}, y_{15}, z_{15})] [R(y_{16})] [T(-x_{15}, -y_{15}, -z_{15})] \| P_{tdp} \| \\
 \| P_i \| &= \| P_{imc} \| [T(x_{21}, y_{21}, z_{21})] [R(x_{22})] [R(y_{22})] [T(-x_{21}, -y_{21}, -z_{21})]
 \end{aligned}$$

$$\begin{aligned} & \| P_{ipp} \| \quad [T(x_{23}, y_{23}, z_{23})] [R(x_{24})] [T(-x_{23}, -y_{23}, -z_{23})] \quad \| P_{imp} \| \\ & [T(x_{25}, y_{25}, z_{25})] [R(x_{26})] [T(-x_{25}, -y_{25}, -z_{25})] \quad \| P_{idp} \| \end{aligned}$$

where

- $\| P_c \|$ - polylines representing the carpal bones
- $\| P_t \|$ - polylines representing the thumb
- $\| P_{tmc} \|$ - polylines representing the metacarpal (MC) of the thumb
- $\| P_{tpp} \|$ - polylines representing the proximal phalanx (PP) of the thumb
- $\| P_{tdp} \|$ - polylines representing the distal phalanx (DP) of the thumb
- $\| P_i \|$ - polylines representing the index
- $\| P_{imc} \|$ - polylines representing the MC of the index
- $\| P_{ipp} \|$ - polylines representing the PP of the index
- $\| P_{imp} \|$ - polylines representing the middle phalanx (MP) of the index
- $\| P_{idp} \|$ - polylines representing the DP of the index
- $[T(x_{11}, y_{11}, z_{11})]$ - translation of joint axes, abduction-adduction (AB-AD) and
flexion-extension (FL-EX), of the MC of the thumb
- $[R(x_{11})]$ - rotation about x axis of the MC of the thumb
- $[R(y_{11})]$ - rotation about y axis of the MC of the thumb
- $[R(z_{11})]$ - rotation about z axis of the MC of the thumb
- $[T(x_{12}, y_{12}, z_{12})]$ - translation of joint axes, AB-AD and FL-EX, of the PP
of the thumb
- $[R(x_{12})]$ - rotation about x axis, FL-EX, of the PP of the thumb

- $[R(y_{12})]$ - rotation about y axis, AB-AD, of the PP of the thumb
- $[T(x_{13}, y_{13}, z_{13})]$ - translation of joint axis, FL-EX, of the DP of the thumb
- $[T(x_{22}, y_{22}, z_{22})]$ - translation of joint axes, AB-AD and FL-EX, of the PP
of the index
- $[R(x_{21})]$ - rotation about x axis, FL-EX, of the PP of the index
- $[R(y_{21})]$ - rotation about y axis, AB-AD, of the PP of the index
- $[T(x_{23}, y_{23}, z_{23})]$ - translation of joint axis, FL-EX, of the MP of the index
- $[R(x_{22})]$ - rotation about x axis, FL-EX, of the MP of the index
- $[T(x_{24}, y_{24}, z_{24})]$ - translation of joint axis, FL-EX, of the DP of the index
- $[R(x_{23})]$ - rotation about x axis, FL-EX, of the DP of the index

Notice that no geometric modeling transformation is applied to the carpal bones since they are at the top of the hierarchical structures. Structures at this position in a hierarchical structure are termed *parent structures*. Structures immediately below these parent structures are termed *children structures*. The viewing transformation can be applied for viewing manipulation, such as window/viewport sizes, projection type, and clipping planes. For the rest of fingers, transformation matrices similar to those for the index are applied. The transformation matrices are hierarchically implemented in the *hand structure* in PHIGS.

In the above transformation all rotation matrices are interactively performed using the virtual dials that have been created using widgets provided by AVS LUI. The dial keeps sending the value to the rotation matrix which is then updated

and affects its children structures. In this way, all rotation parameters such as x_{12} , y_{12} , z_{12} , x_{14} , and so on are changed every time the dials are rotated. This is how the joint is rotated interactively.

Figure 3.1 shows the hand image in the resting position on a Stardent GS1000. In this position the rotation parameters are initialized to zero. Figure 3.2 shows the hand with each joint rotated.

3.2 Interactive Graphical Modeling of the Hand

3.2.1 PHIGS

The major impediment restricting the portability of computer graphics applications has been the wide variety of graphics hardware and the softwares' dependency on the hardware [33]. Therefore, a device-independent, interactive graphics system for complex geometric modeling was felt to be essential to real progress in the field of engineering and scientific computer graphics. The first device-independent computer graphics standard at the programmer-interface level was the Graphical Kernel System (GKS) that was originally developed as a two-dimensional international graphics standard by the International Standards Organization (ISO).

PHIGS is the second graphics standard after GKS and its 3D extensions were designed to be the interaction toolset for graphical model building and manipulation [32]. It utilizes and builds on many GKS concepts, including primitives and attribute types, but it adds new and powerful concepts such as *structures*



Figure 3.1: A Stardent GS1000 display of the hand. The images are obtained from 172 nonoverlapping CT slices spaced 1 mm apart.



Figure 3.2: The hand with each joint rotated.

and *structure editing* [3]. In other words, the power of PHIGS comes from how the primitives and attributes it provides are organized and manipulated[32]. The following are unique among features that PHIGS has[2].

- Hierarchical graphic data organization.
- Structure editing.

Structure Hierarchy

The most important feature in PHIGS is the *hierarchy* of the objects. The useful consequences of hierarchy are as follows [2]:

- Definition of a complex object with a relatively small amount of graphic information.
- Structure consistency.
- Attribute inheritance - Traversal time attribute binding, rather than structure creation time attribute binding.

A structure hierarchy is created by using a structure element called **EXECUTE**. Figure 3.3 shows a simple structure with hierarchical graphic data organization. Structure 1 invokes (executes) structures 2, 3, and 4. Structures 2 and 3 both invoke structure 5 that invokes structure 8. Also structures 6 and 7 are invoked by structure 4. Figure 3.4 shows the structure hierarchy of the hand used in this work.

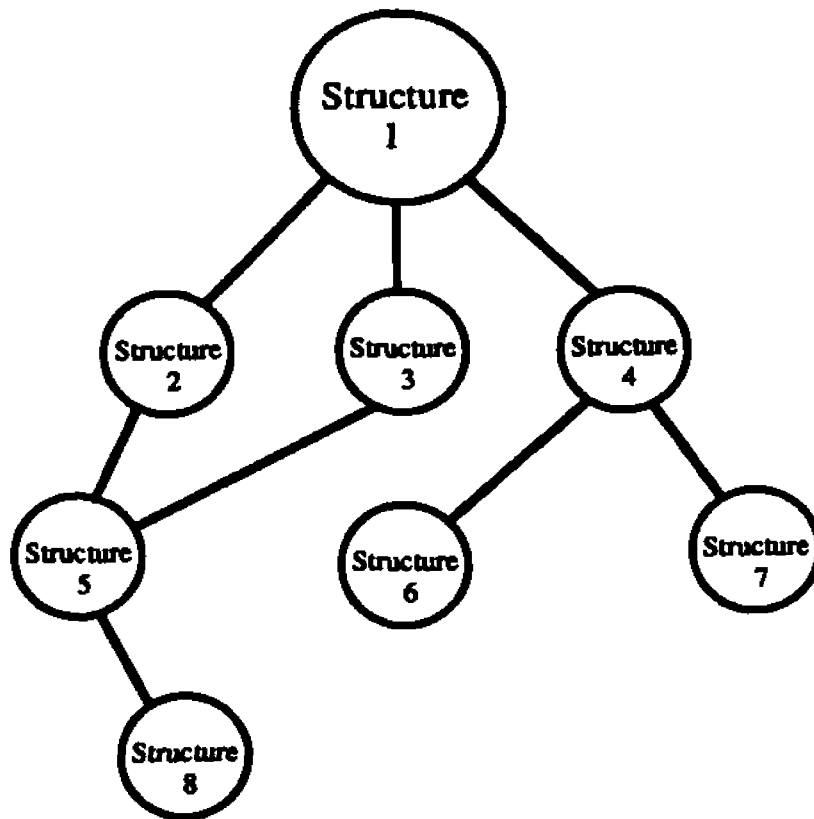


Figure 3.3: An example structure showing hierarchical graphic data organization.

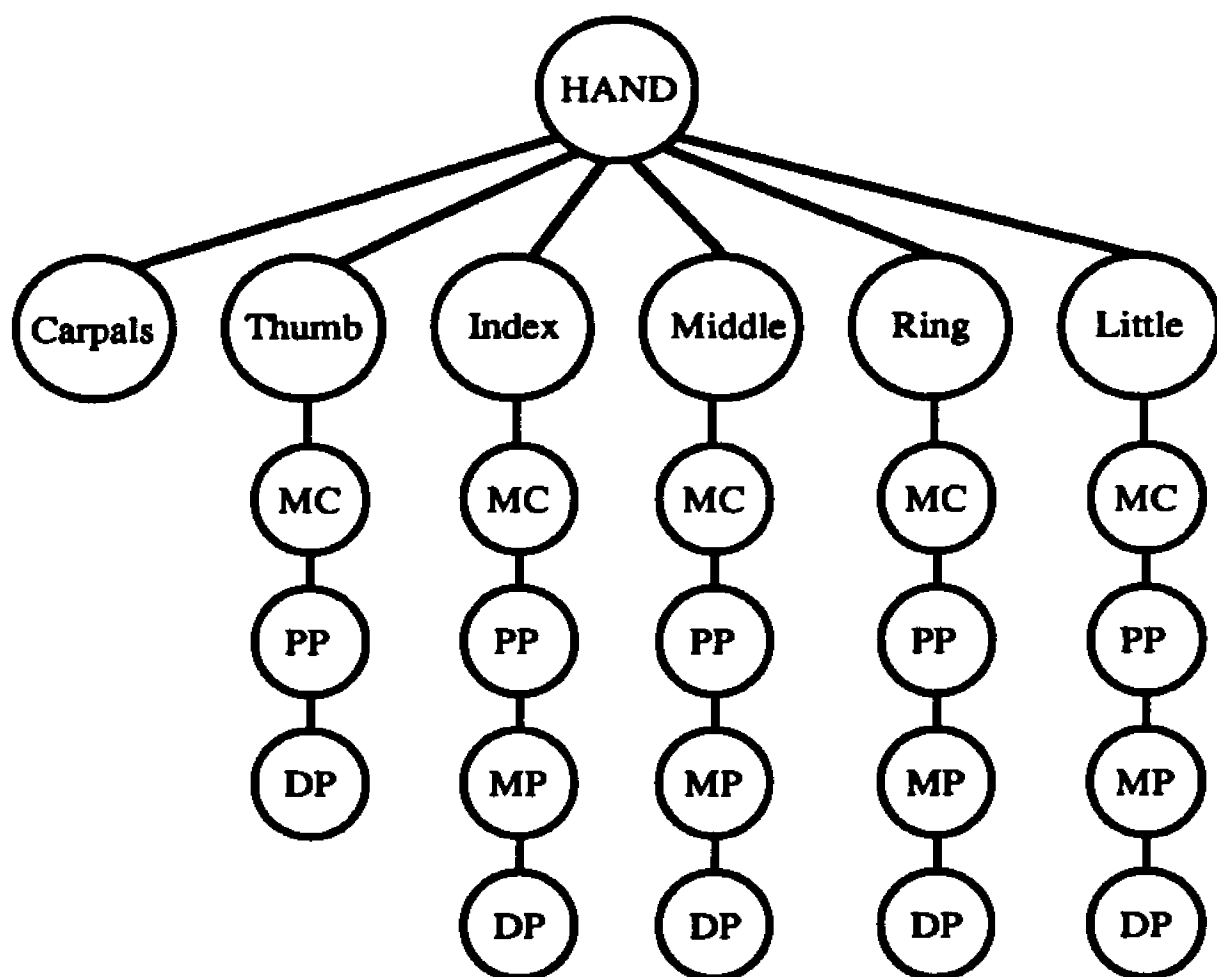


Figure 3.4: The structure hierarchy of the hand used in this work.

This concept can be applied to the hand as shown in the following pseudo-code for an index finger.

```

/* Pseudo-code 1 */

/* open a structure to be edited */
OPEN STRUCTURE (INDEX FINGER)

    /* place a label that can be used to address */
    /* the element SET POLYLINE COLOR */
    INSERT LABEL (LABEL0)

    /* put SET POLYLINE COLOR element */
    INSERT SET POLYLINE COLOR (RGB, COLOR1)

    /* invoke the first highest hierarchy of */
    /* structure INDEX FINGER */
    EXECUTE STRUCTURE (METACARPAL)

    /* place a label that can be used to address */
    /* the element ROTATE X */
    INSERT LABEL (LABEL1)

    /* put an element ROTATE X that will be used */
    /* to rotate in X the following structures, such as */
    /* PROXIMAL, MIDDLE, and DISTAL PHALANX */
    INSERT ROTATE X (0, PRECONCATEENATE)

    /* place a label that can be used to address */
    /* the element ROTATE Y */
    INSERT LABEL (LABEL2)

    /* put an element ROTATE Y that will be used */
    /* to rotate in Y the following structures, such as */
    /* PROXIMAL, MIDDLE, and DISTAL PHALANX */
    INSERT ROTATE Y (0, PRECONCATEENATE)

    /* invoke the second highest hierarchy of */
    /* structure INDEX FINGER */
    EXECUTE STRUCTURE (PROXIMAL PHALANX)

    /* place a label that can be used to address */

```

```

/* the element ROTATE X */
INSERT LABEL (LABEL3)

/* put an element ROTATE X that will be used to */
/* rotate in X the following structures, i.e., */
/* MIDDLE PHALANX and DISTAL PHALANX */
INSERT ROTATE X (0, PRECONCATENATE)

/* third highest hierarchy of structure INDEX FINGER */
EXECUTE STRUCTURE (MIDDLE PHALANX)

/* place a label that can be used to address */
/* the element ROTATE X */
INSERT LABEL (LABEL4)

/* put an element ROTATE X that will be used to */
/* rotate in X the DISTAL PHALANX only */
INSERT ROTATE X (0, PRECONCATENATE)

/* lowest hierarchy of structure INDEX FINGER */
EXECUTE STRUCTURE (DISTAL PHALANX)

/* once opened, a structure must be closed */
CLOSE STRUCTURE

```

Structure Editing

All structure elements can be copied, modified, added, or deleted using structure editing. The structure elements can be either output primitives, attributes, labels, name set specifications, application data, transformations, viewing definition, or structure invocations. To edit a structure, first the structure must be opened, which automatically causes the structure elements pointer to address the last element in the structure. Elements can be added after the last element, or the last element pointed can be deleted. Other elements also can be addressed by equating an element pointer to the specified label.

In pseudo-code 1, the color of structures *METACARPAL*, *PROXIMAL PHALANX*, *MIDDLE PHALANX*, and *DISTAL PHALANX* can be changed from COLOR1 to COLOR2 as follows:

```

/* Pseudo-code 2 */

/* open the structure that includes structures to be edited */
OPEN STRUCTURE (INDEX FINGER)

    /* find the nearest label to the element */
    /* SET POLYLINE COLOR */
    SET ELEMENT POINTER AT LABEL (LBELO)

    /* move the pointer one element down and address */
    /* the element SET POLYLINE COLOR */
    OFFSET ELEMENT POINTER (1)

    /* delete the current SET POLYLINE COLOR element */
    /* that has color1 */
    DELETE ELEMENT

    /* put a new element SET POLYLINE COLOR that has */
    /* color2 so that color1 can change to color2 */
    INSERT SET POLYLINE COLOR (RGB, COLOR2)

/* close the structure */
CLOSE STRUCTURE

/* redraw structures */
REDRAW ALL STRUCTURES (WORKSTATION ID, ALWAYS)

```

Or the structure *DISTAL PHALANX* can be rotated 90 degree in X direction as follows:

```

/* Pseudo-code 3 */

/* open the structure that includes structures to be edited */

```

OPEN STRUCTURE (INDEX FINGER)

```

/* find the nearest label to ROTATE X element that is */
/* used to rotate the DISTAL PHALANX only */
SET ELEMENT POINTER AT LABEL (LABEL4)

/* move the pointer one element down and address */
/* the element ROTATE X */
OFFSET ELEMENT POINTER (1)

/* delete the current ROTATE X element */
DELETE ELEMENT

/* put a new element ROTATE X that has 90 so that */
/* the structure DISTAL PHALANX can be rotated */
/* 90 degree in x */
INSERT ROTATE X (90, PRECONCATENATE)

/* close the structure */
CLOSE STRUCTURE

/* redraw structures */
REDRAW ALL STRUCTURES (WORKSTATION ID, ALWAYS)

```

3.3 Math Modeling of Muscle and Tendon

“The output of a muscle is tension”[11]. The tension comes from two different biological mechanisms of muscle fibers, *active contraction* and *passive elastic recoil* after being stretched. The active contraction is obtained by the sarcomeres in the muscle fiber. The muscle fibers consist of a number of sarcomeres which in turn are composed of many filaments of actin and myosin. Each sarcomere is identical to all others in generating force and excursion regardless of the size of the muscle. In other words, the number of sarcomeres and how they are arranged determine the size and strength of the muscle.

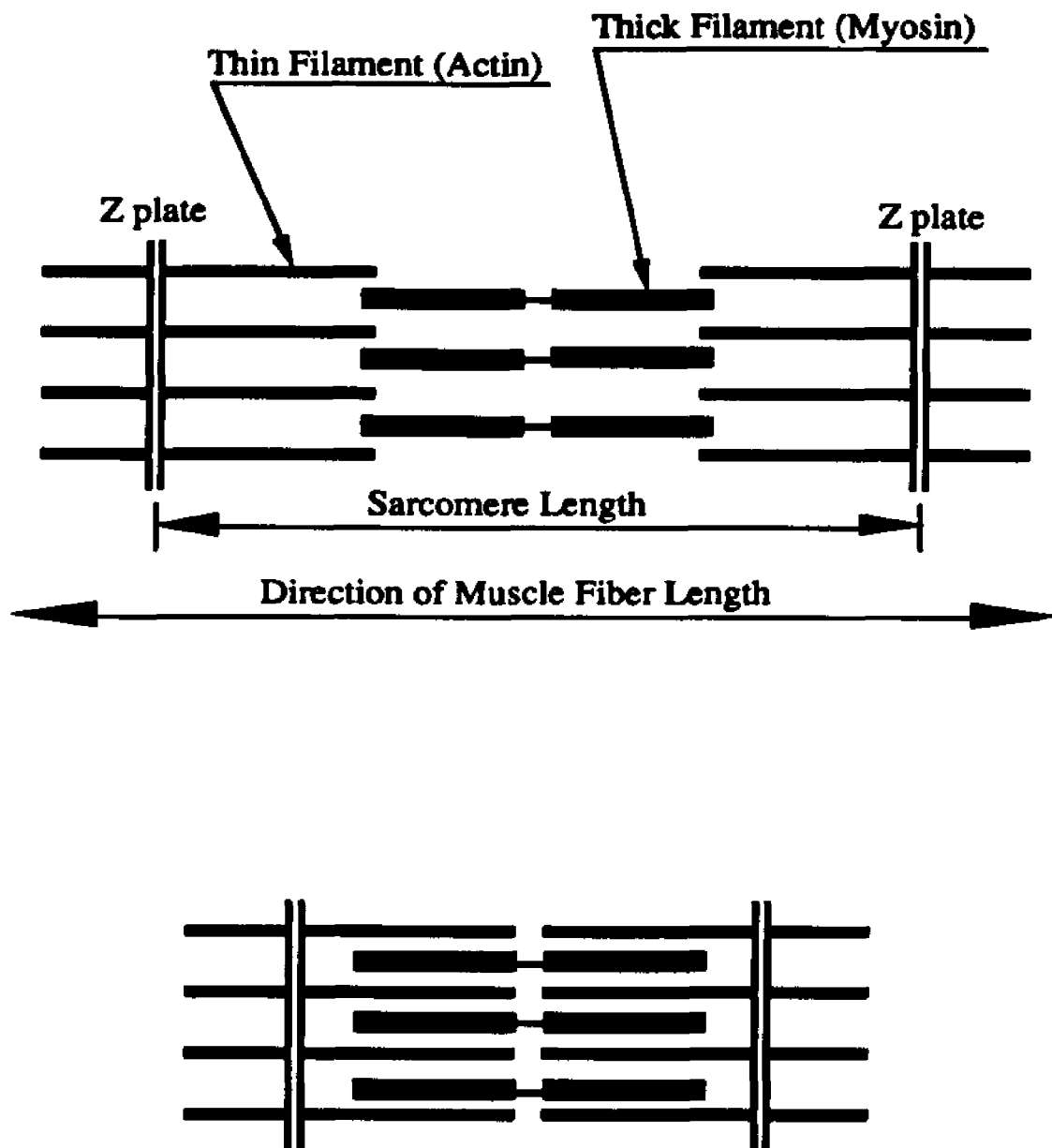


Figure 3.5: Basic structure of sarcomere when the muscle fiber is stretched (above) and when it is contracted (below). Adapted from [11]. Muscle fibers are composed of long series of sarcomeres.

Figure 3.5 describes the basic structures of sarcomere and muscle fiber. The space between actin and myosin filaments is where the tension is created and the shortening or lengthening of the muscle takes place. Therefore the maximum contraction is generated by the maximum overlap between actin and myosin filaments. The sarcomere length is the distance between the Z plates. It can vary from about $1.5\mu m$ to $4.0\mu m$, depending whether it is at full shortening or at full lengthening.

The structure of the muscle is such that many filaments are in parallel and many sarcomeres are in series to make up a single contractile element. It is due to the *elastic* behavior of a musculotendon unit, not just the stimulus of the CNS that shortens a muscle when the unit is stretched by a large external force and then released. In particular, the muscle, even though it is at its resting length, shortens when it is detached from the insertion. This state of tension when it is in the resting position is, however, not due to its *passive elasticity* but to the continual stimulation of the muscle by the CNS.

The muscle, however, has another characteristic of *viscoelasticity* as well. It can be deduced from the fact that the muscle behaves differently when a muscle is rapidly distended than when slow movement is applied. This is the result of a damping effect in the muscle. Therefore, *viscoelasticity* is a more appropriate term than *elasticity* in characterizing the muscle for rapid motions.

Figure 3.6 illustrates the mechanical representation of a musculotendon unit

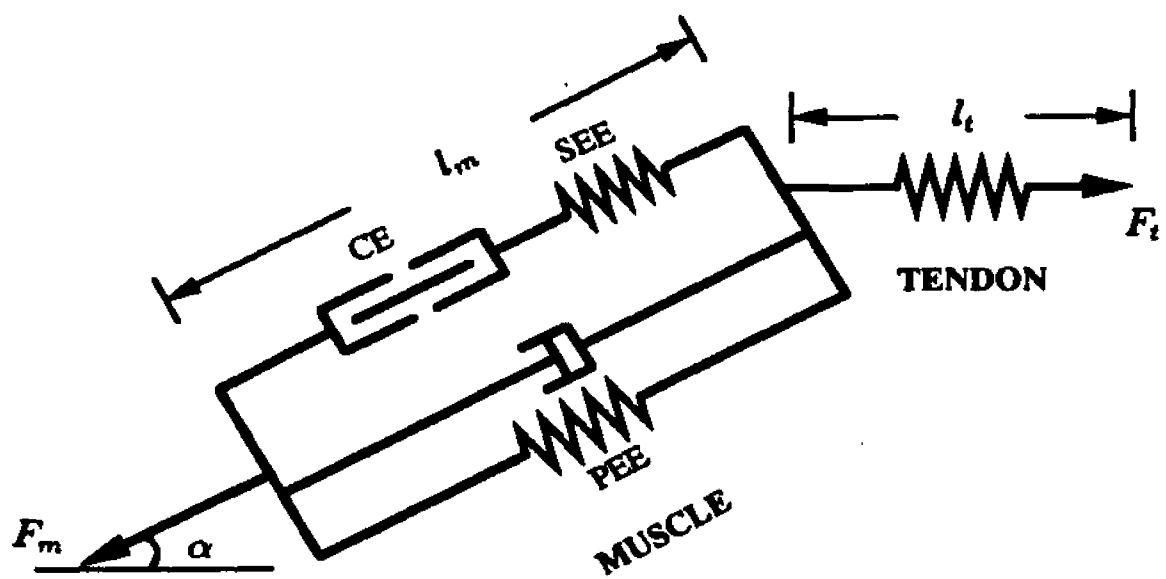


Figure 3.6: Mechanical representation of a musculotendon unit based on Hill's concept.

based on Hill's concept [38,23,11]. The muscle is considered to consist of a *contractile element* (CE), a *series elastic element* (SEE), and a *parallel elastic element* (PEE). As shown in Figure 3.6 the latter element is composed of a damping and an elastic component. The damping element contributes to the viscoelastic effect on the musculotendon unit. The elements CE and PEE are considered to generate the muscle force.

The angle α is the pennation angle which is assumed to be zero in this work since all muscles under consideration are assumed to be fusiform instead of being pennated. This assumption is made on the basis that mono-pennated muscles *in situ* behave much like fusiform muscles do. The element SEE in Figure 3.6 can also be disregarded because of its very small adaptability that allows sarcomeres to shorten during isometric contraction of muscle. Viscoelastic effects cannot be neglected for the human body in fast motion such as a pianist's fingers, a baseball pitcher's arm, or a sprinter's legs. In this work focused on the static properties of the musculotendon unit, it is assumed that the muscle fiber is an elastic element rather than viscoelastic, and thus the dynamic properties of the muscle fiber have much less influence on the unit than do the static properties.

With the assumptions made above the simplified musculotendon unit can be described as in Figure 3.7. Figure 3.8 shows that the normalized length-force diagram of a muscle fiber, which is a modified form of the *Bliz curve*[11]. The abscissa describes the normalized muscle fiber length, that is, the muscle fiber

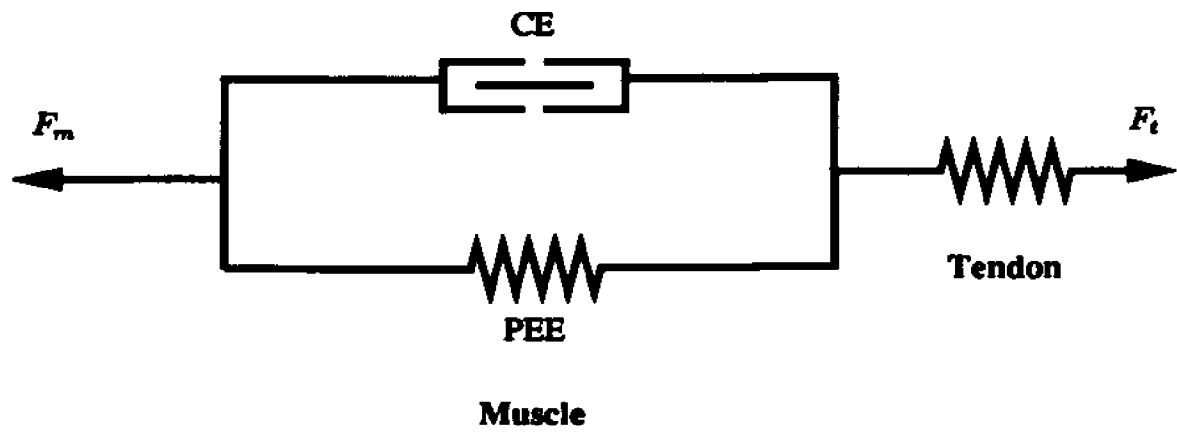


Figure 3.7: Simplified mechanical representation of a musculotendon unit as modeled in this work.

length (l_m) normalized by its resting length (l_{om}), and the ordinate represents the normalized muscle force, the muscle force (F_m) normalized by the maximum isometric muscle force (F_{max}).

The resting length of muscle fiber, denoted by l_{om} , is the length that the muscle fiber assumes in its resting and balanced condition. It is noteworthy that the maximum active muscle force during contraction occurs not when it is stretched but when it is at its resting length, that is, $\frac{l_m}{l_{om}} = 1$, and the maximum normalized potential excursion of muscle, L , is the distance between the fully stretched length and fully contracted length.

A group of downward concave thin solid lines in Figure 3.8 represents the active muscle force resulting from active contraction which depends on the degree of activation of the Central Nervous System (CNS), denoted by ξ . Thus, the maximum active normalized muscle force may vary from $\xi = 0$ to $\xi = 1$. In Figure 3.6 and Figure 3.7, the contractile element (CE) generates the active muscle force.

The thin shaded line in Figure 3.8 shows the passive muscle force resulted from elasticity in the connective tissue that surrounds the contractile element, that is, the parallel elastic element (PEE) in Figure 3.6 and Figure 3.7. It behaves much like an elastic rubber band. When it is at resting length or less, it is in a slack state with no tension. However, as the muscle lengthens, it is no longer in a slack state, so tension begins to build up slowly at first and then rapidly. In

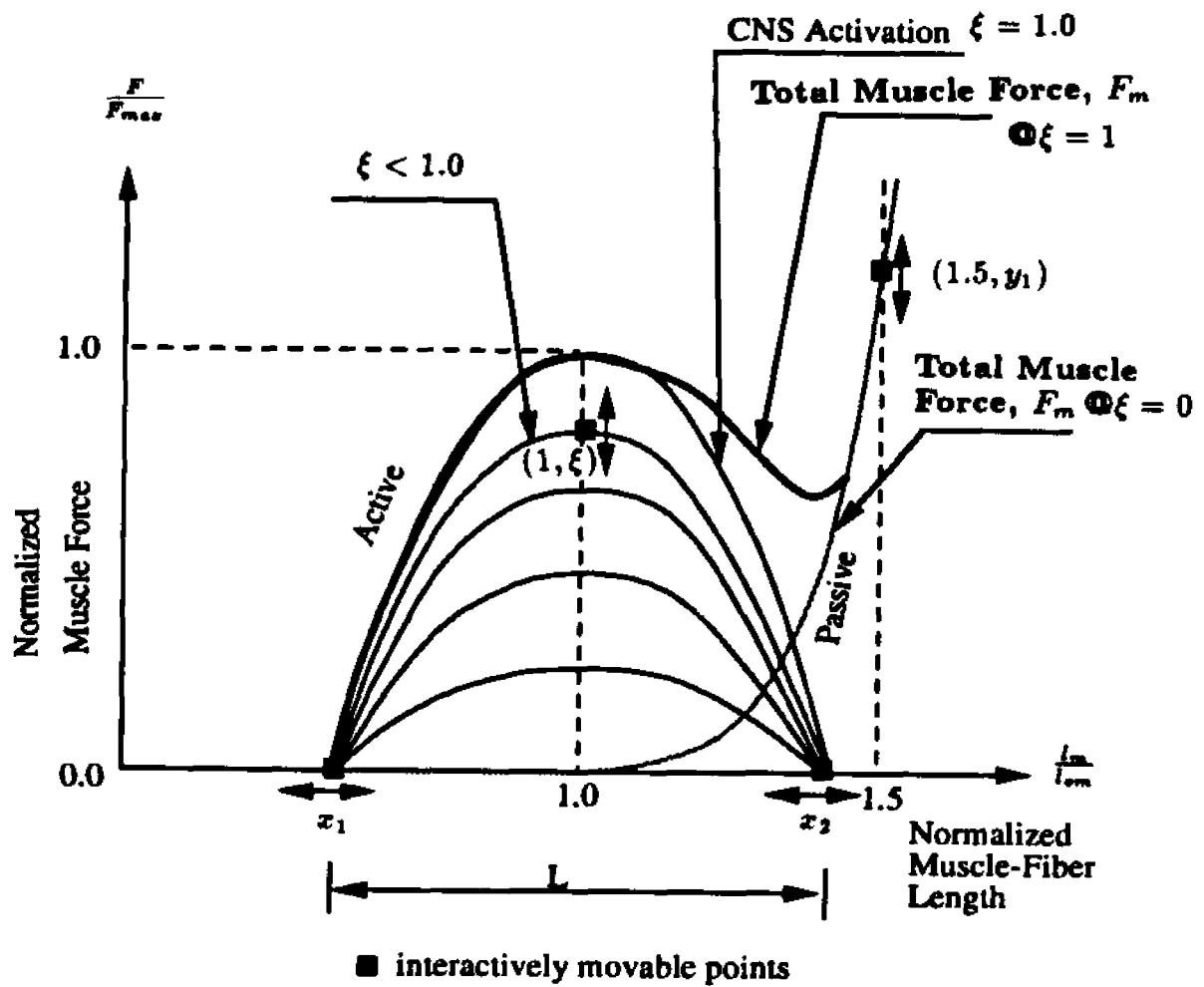


Figure 3.8: Normalized length-force diagram of a muscle fiber, modified *Bliz* curve. ξ , x_1 , x_2 , and y_1 are physiological parameters that can be interactively changed.

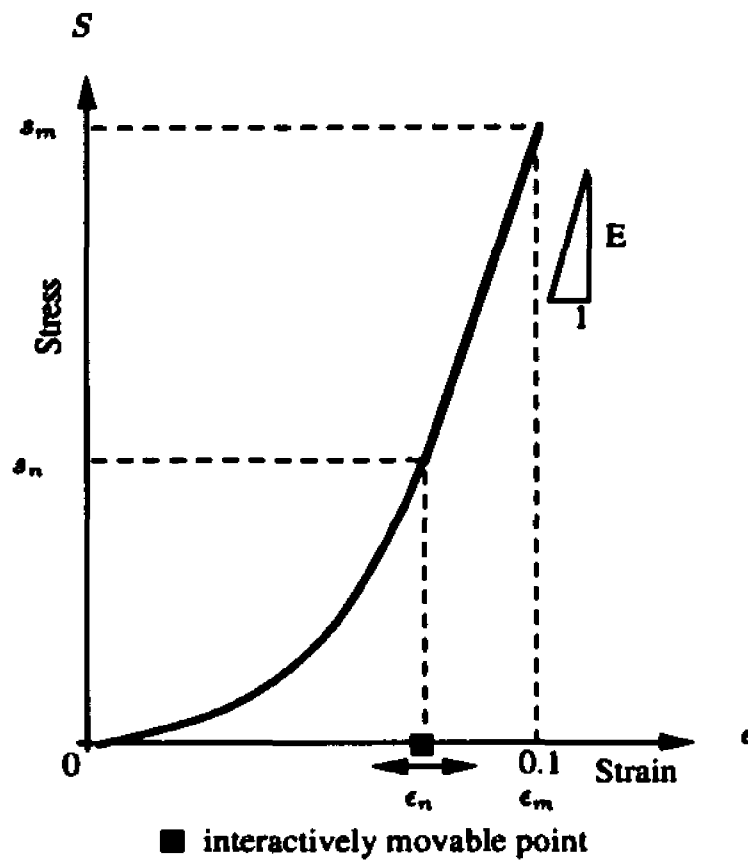


Figure 3.9: Stress-strain diagram of a tendon. ϵ_n is a physiological parameter that can be interactively changed.

other words, unlike the rubber band, the passive muscle force is nonlinear. Note that the passive muscle force is not affected by ξ .

In reality, the Blix curve¹ is not symmetric about the center line of the curve, as shown in Figure 3.8. The reason why such a simple function was chosen to represent the normalized length-force diagram of a muscle fiber and the stress-strain diagram of a tendon is as follows:

- to reduce the number of parameters of the model and make these parameters have physical meaning.
- to increase the speed of calculation by providing an analytic solution rather than an iterative solution.
- to be able to change muscle and tendon physical parameters easily and dynamically

In Figure 3.8, the active muscle force, F_{am} , can be assumed to be represented as

$$\frac{F_{am}}{F_{max}} - \xi = -\frac{4\xi}{L^2} \left(\frac{l_m}{l_{om}} - 1 \right)^2,$$

that is,

$$\frac{F_{am}}{F_{max}} = \xi \left[1 - \frac{4}{L^2} \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right]$$

and the passive muscle force, F_{pm} , is assumed as

$$\frac{F_{pm}}{F_{max}} = 4y_1 \left(\frac{l_m}{l_{om}} - 1 \right)^2.$$

¹Refer to Brand[11], page 17, Figure 3-8.

When muscle is contracted and becomes shorter than its resting length, the passive muscle force is not produced and only the active muscle force will result. If one normalizes the muscle force to that at the resting length, this becomes:

$$\frac{F_m}{F_{max}} = \xi \left[1 - \frac{4}{L^2} \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right] \quad \left(x_1 \leq \frac{l_m}{l_{om}} \leq 1 \right) \quad (3.1)$$

When muscle is stretched beyond its resting length and ready for active contraction, total normalized muscle force will be the sum of the active muscle force by CE and the passive muscle force by PEE because the both muscle forces are exerted in the same direction. Therefore,

$$\frac{F_m}{F_{max}} = \xi \left[1 - \frac{4}{L^2} \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right] + 4y_1 \left(\frac{l_m}{l_{om}} - 1 \right)^2 \quad \left(1 \leq \frac{l_m}{l_{om}} \leq x_2 \right) \quad (3.2)$$

where

F_{max} = maximum isometric muscle force

F_m = force in muscle

l_{om} = resting length of muscle fiber

l_m = length of muscle fiber

y_1 = physiological elasticity parameter of muscle

ξ = degree of activation of the muscle by CNS

L = maximum normalized potential excursion of the muscle

The thick solid line in Figure 3.8 is the total muscle force with full CNS activation.

Multiplying by F_{max} on both sides of Equations 3.1 and 3.2, the force in the muscle becomes

$$F_m = \begin{cases} F_{max} \left[\xi \left(1 - \frac{4}{L^2} \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right) \right] & (x_1 \leq \frac{l_m}{l_{om}} \leq 1) \\ F_{max} \left[\xi \left(1 - \frac{4}{L^2} \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right) + 4y_1 \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right] & (1 \leq \frac{l_m}{l_{om}} \leq x_2) \end{cases} \quad (3.3)$$

As shown in Figure 3.9 the stress-strain diagram for the tendon is of the same shape as that of muscle fiber during passive stretch but tendons are much less extensible than muscle. The stress-strain diagram for the tendon is modeled by the following function.

$$s = \begin{cases} s_n \left(\frac{\epsilon}{\epsilon_n} \right)^2 & (0 \leq \epsilon \leq \epsilon_n) \\ s_n + E(\epsilon - \epsilon_n) & (\epsilon_n \leq \epsilon \leq \epsilon_m) \end{cases} \quad (3.4)$$

where

s = stress

ϵ = strain = $\frac{l_t - l_{ot}}{l_{ot}}$

ϵ_m = maximal physiologic strain, 0.1 (Adapted from Zajac[38])

ϵ_n = upper limit of nonlinear stress-strain response of tendon

l_t = length of tendon (tendon origin to insertion)

l_{ot} = resting length of tendon

E = modulus of elasticity of tendon.

Differentiating the first equation in Equation 3.4 with respect to ϵ yields

$$\left. \frac{ds}{d\epsilon} \right|_{\epsilon=\epsilon_n} = 2 \frac{s_n}{\epsilon_n} = E \quad (3.5)$$

Thus,

$$s_n = \frac{1}{2} E \epsilon_n \quad (3.6)$$

Since, as shown in Figure 3.9 E is the slope of the linear portion of the curve, one may write

$$E = \frac{s_m - s_n}{\epsilon_m - \epsilon_n} \quad (3.7)$$

Substituting Equation 3.6 into Equation 3.7 yields

$$E = \frac{2s_m}{2\epsilon_m - \epsilon_n} \quad (3.8)$$

Meanwhile, multiplying Equation 3.4 by A/F_{max} where A is a physiological cross sectional area of a tendon and rearranging gives

$$\frac{sA}{F_{max}} = \frac{F_t}{F_{max}} = \begin{cases} \frac{s_n A}{F_{max}} \left(\frac{\epsilon}{\epsilon_n}\right)^2 & (0 \leq \epsilon \leq \epsilon_n) \\ \frac{s_n A}{F_{max}} + \frac{EA}{F_{max}} (\epsilon - \epsilon_n) & (\epsilon_n \leq \epsilon \leq \epsilon_m) \end{cases} \quad (3.9)$$

where F_t is the force or tension of the tendon.

Introducing an equivalent safety factor, K , defined as

$$K = \frac{s_m}{F_{max}/A},$$

Equation 3.9 becomes

$$\frac{F_t}{F_{max}} = \begin{cases} K \frac{s_n}{s_m} \left(\frac{\epsilon}{\epsilon_n}\right)^2 & (0 \leq \epsilon \leq \epsilon_n) \\ K \frac{s_n}{s_m} + \frac{KE}{s_m} (\epsilon - \epsilon_n) & (\epsilon_n \leq \epsilon \leq \epsilon_m) \end{cases} \quad (3.10)$$

where F_t is the tension in the tendon.

Substituting Equations 3.6 and 3.7 into Equation 3.10 and rewriting, Equation 3.10 becomes

$$F_t = \begin{cases} F_{max} \left[\left(\frac{K}{2\epsilon_m - \epsilon_n} \right) \left(\frac{\epsilon^2}{\epsilon_n} \right) \right] & (0 \leq \epsilon \leq \epsilon_n) \\ F_{max} \left[K \left(\frac{2\epsilon - \epsilon_n}{2\epsilon_m - \epsilon_n} \right) \right] & (\epsilon_n \leq \epsilon \leq \epsilon_m) \end{cases} \quad (3.11)$$

Since

$$\epsilon = \frac{l_t - l_{ot}}{l_{ot}},$$

Equation 3.11 becomes

$$F_t = \begin{cases} F_{max} \left[\left(\frac{K}{2\epsilon_m - \epsilon_n} \right) \left(\frac{1}{\epsilon_n} \right) \left(\frac{l_t - l_{ot}}{l_{ot}} \right)^2 \right] & (1 \leq \frac{l_t}{l_{ot}} \leq (1 + \epsilon_n)) \\ F_{max} \left(\frac{K}{2\epsilon_m - \epsilon_n} \right) \left[\frac{2(l_t - l_{ot})}{l_{ot}} - \epsilon_n \right] & ((1 + \epsilon_n) \leq \frac{l_t}{l_{ot}} \leq (1 + \epsilon_m)) \end{cases} \quad (3.12)$$

Total length of the musculotendon unit, l_{total} , is a function of a geometry for a given position of the joint of the fingers and it will be known when the tendon path is drawn.

$$l_{total} = l_m + l_t \quad (3.13)$$

Therefore,

$$l_t = l_{total} - l_m \quad (3.14)$$

Substituting Equation 3.14 into Equation 3.12 yields

$$F_t = \begin{cases} F_{max} \left[\left(\frac{K}{2\epsilon_m - \epsilon_n} \right) \left(\frac{1}{\epsilon_n} \right) \left(\frac{l_{total} - l_m - l_{ot}}{l_{ot}} \right)^2 \right] & (1 \leq \frac{l_t}{l_{ot}} \leq (1 + \epsilon_n)) \\ F_{max} \left(\frac{K}{2\epsilon_m - \epsilon_n} \right) \left[\frac{2(l_{total} - l_m - l_{ot})}{l_{ot}} - \epsilon_n \right] & ((1 + \epsilon_n) \leq \frac{l_t}{l_{ot}} \leq (1 + \epsilon_m)) \end{cases} \quad (3.15)$$

As mentioned before, the pennation angle α is assumed to be zero in this work. With this assumption, the forces in muscle and tendon in Equations 3.3 and 3.15 are identical so that the following relationship can be obtained.

$$F_m = F_t \quad (3.16)$$

Using the above relationship and Equation 3.15, four cases can be considered

to find l_m as follows:

$$\begin{aligned}
 &\text{Case 1: } x_1 \leq \frac{l_m}{l_{om}} \leq 1 \text{ and } 1 \leq \frac{l_t}{l_{ot}} \leq (1 + \epsilon_n) \\
 &\xi \left[1 - \frac{4}{L^3} \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right] = \left(\frac{K}{2\epsilon_m - \epsilon_n} \right) \left(\frac{1}{\epsilon_n} \right) \left(\frac{l_{total} - l_m - l_{ot}}{l_{ot}} \right)^2 \\
 &\text{Case 2: } x_1 \leq \frac{l_m}{l_{om}} \leq 1 \text{ and } (1 + \epsilon_n) \leq \frac{l_t}{l_{ot}} \leq (1 + \epsilon_m) \\
 &\xi \left[1 - \frac{4}{L^3} \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right] = \left(\frac{K}{2\epsilon_m - \epsilon_n} \right) \left[\frac{2(l_{total} - l_m - l_{ot})}{l_{ot}} - \epsilon_n \right] \\
 &\text{Case 3: } 1 \leq \frac{l_m}{l_{om}} \leq x_2 \text{ and } 1 \leq \frac{l_t}{l_{ot}} \leq (1 + \epsilon_n) \\
 &\xi \left[1 - \frac{4}{L^3} \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right] + 4y_1 \left(\frac{l_m}{l_{om}} - 1 \right)^2 = \left(\frac{K}{2\epsilon_m - \epsilon_n} \right) \left(\frac{1}{\epsilon_n} \right) \left(\frac{l_{total} - l_m - l_{ot}}{l_{ot}} \right)^2 \\
 &\text{Case 4: } 1 \leq \frac{l_m}{l_{om}} \leq x_2 \text{ and } (1 + \epsilon_n) \leq \frac{l_t}{l_{ot}} \leq (1 + \epsilon_m) \\
 &\xi \left[1 - \frac{4}{L^3} \left(\frac{l_m}{l_{om}} - 1 \right)^2 \right] + 4y_1 \left(\frac{l_m}{l_{om}} - 1 \right)^2 = \left(\frac{K}{2\epsilon_m - \epsilon_n} \right) \left[\frac{2(l_{total} - l_m - l_{ot})}{l_{ot}} - \epsilon_n \right]
 \end{aligned} \tag{3.17}$$

where the only unknown parameter in the above equations is l_m and other parameters are known.

Each case can be solved for l_m and l_t can be found using Equation 3.14. After getting l_m and l_t , for each case, the correct l_m and l_t can be obtained by checking them to see if they satisfy the appropriate inequality. With l_m and l_t , either Equations 3.3 or 3.15 can be solved for F_t or F_m , which are equal.

What has been presented here is a generic musculotendon model that can be scaled by a few parameters to represent a specific model. The parameters which can be interactively changed for this scaling are:

- maximum isometric muscle force (F_{max})
- resting length of muscle fiber (l_{om})
- total length of musculotendon unit (l_{total})
- CNS activation (ξ)

- equivalent safety factor (K)
- upper limit of nonlinear stress-strain response of tendon (ϵ_n)
- physiological elasticity parameter of muscle (y_1)
- maximum normalized potential excursion of muscle (L)

All of these can be interactively changed and are properties of the musculo-tendon system with the exception of the CNS activation, ξ . This is a variable determined by the control algorithm of the central nervous system. At this writing, this control algorithm is not well understood.

Chapter 4

Tendon Path Planning

4.1 An Example of Simulation

Figures 4.2 through 4.7 show a series of graphical simulation sessions. In the following paragraphs, a brief description on an example simulation session is introduced.

Displaying the hand: Figure 4.2 shows the initial display of the hand in its *resting position*, along with the main menu button pad. Thus, all of the joint angles are initially set to zero. As shown in Figure 4.1, the x axis runs ulnarly, y runs dorsally, and z runs distally. This hand is composed of a large number of closed polylines that were derived from CT scans[29]. Using the virtual dials, the hand display can be either rotated or translated.

Figure 4.3 shows the hand rotated -90 degrees about the x axis and 90 degrees about the y axis. The display screen conforms to a right-handed coordinate system.

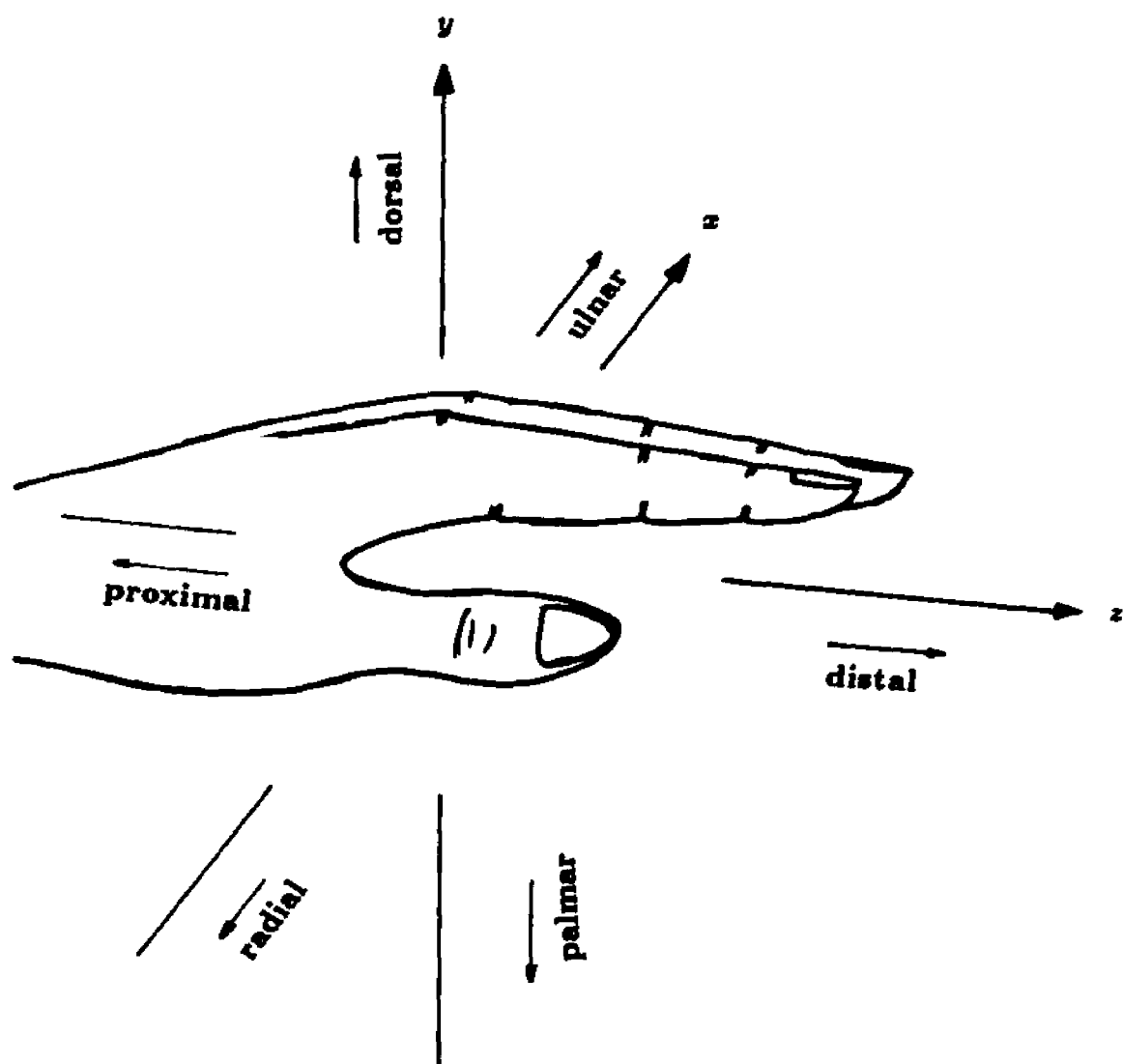


Figure 4.1: The coordinate system of the hand

Selecting points and drawing path: The tendon path points are selected with two orthogonal three-dimensional cursors. One 3D cursor can be translated only in the xy plane. In other words, its z coordinate is always zero. The other 3D cursor can move only in the yz plane, thus its x coordinate is always zero. When these two cursors pick up two points that look different but are identical in space, The first cursor tells the user x and y coordinates of the point and the second tells y and z where both y 's are the same.

The reason why two orthogonal cursors are used to pick up a point, instead of one, is to eliminate the difficulty of picking up a point when the cursor is positioned obliquely on the 2D screen. It is not easy for the user to recognize whether the cursor is moving out of the screen or into the screen. However, since two cursors move only either horizontally or vertically on the screen, the user will not have difficulty when picking points.

Figure 4.4 shows two orthogonal displays of the hand along with two orthogonal cursors. For the coordinate system of the cursor on left, the x axis is inward from the screen, y axis is upward, and z axis is to the right. For the cursor on right, x axis is to the right, y axis is upward, and z axis is outward from the screen.

Figure 4.5 shows the procedure of picking up the tendon path points. Before drawing the tendon path the user is able to delete the points selected and add new points as he wants. The tendon path consists of straight and curved line

segments. In general, a part of the path running across the joint is represented by curved line segments and the rest of the path is represented by straight line segments. The tendon path points which are logically attached on the same bone have no relative movement. Figure 4.6 shows the initial tendon path that is the path for the finger in resting position.

Rotating joints and defining input parameters: After drawing the initial tendon path, new tendon paths can be drawn as the user rotates the joint so that he is able to see how the tendon path changes and what the tendon excursion is. After entering parameters such as the maximum active muscle force (F_{max}), the resting length of muscle fiber (l_{om}), total length of musculotendon unit (l_{total}), and CNS activation (ξ), the user can obtain the result as shown in Figure 4.11 along with a log file.

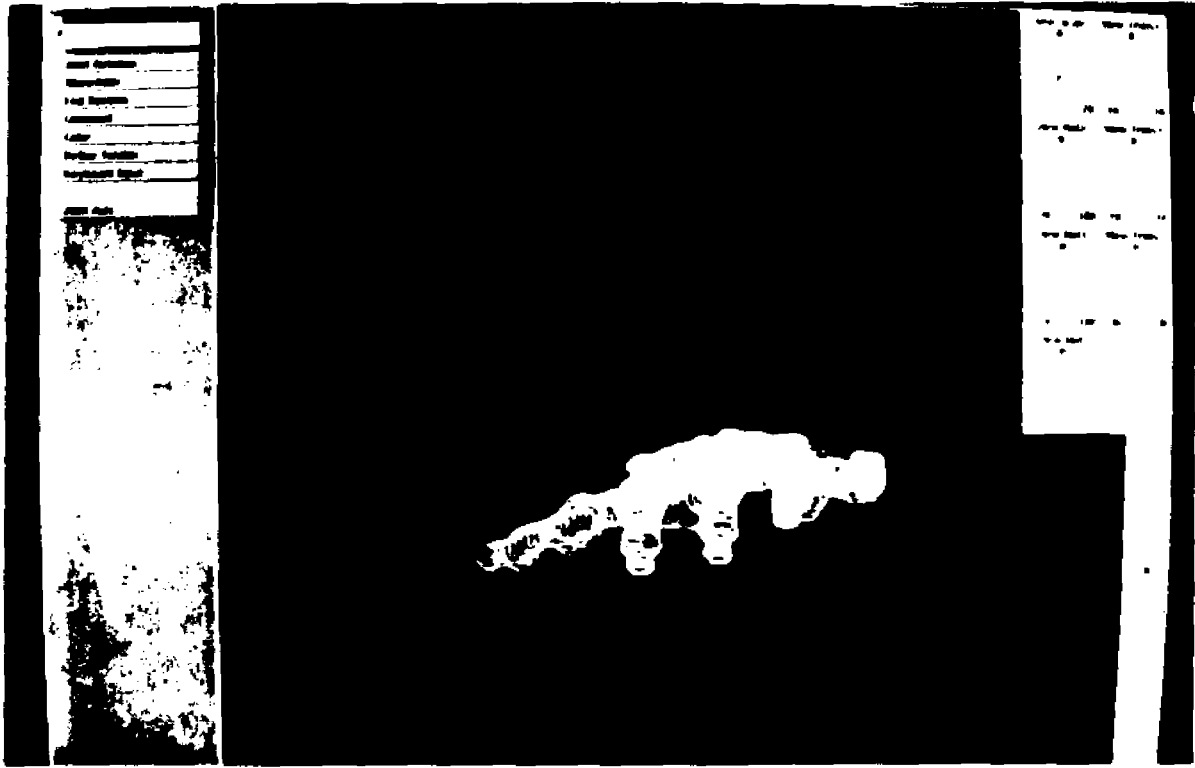


Figure 4.2: The display of the hand in resting position



Figure 4.3: The hand that is rotated -90 degree about x axis and 90 degree about y axis.

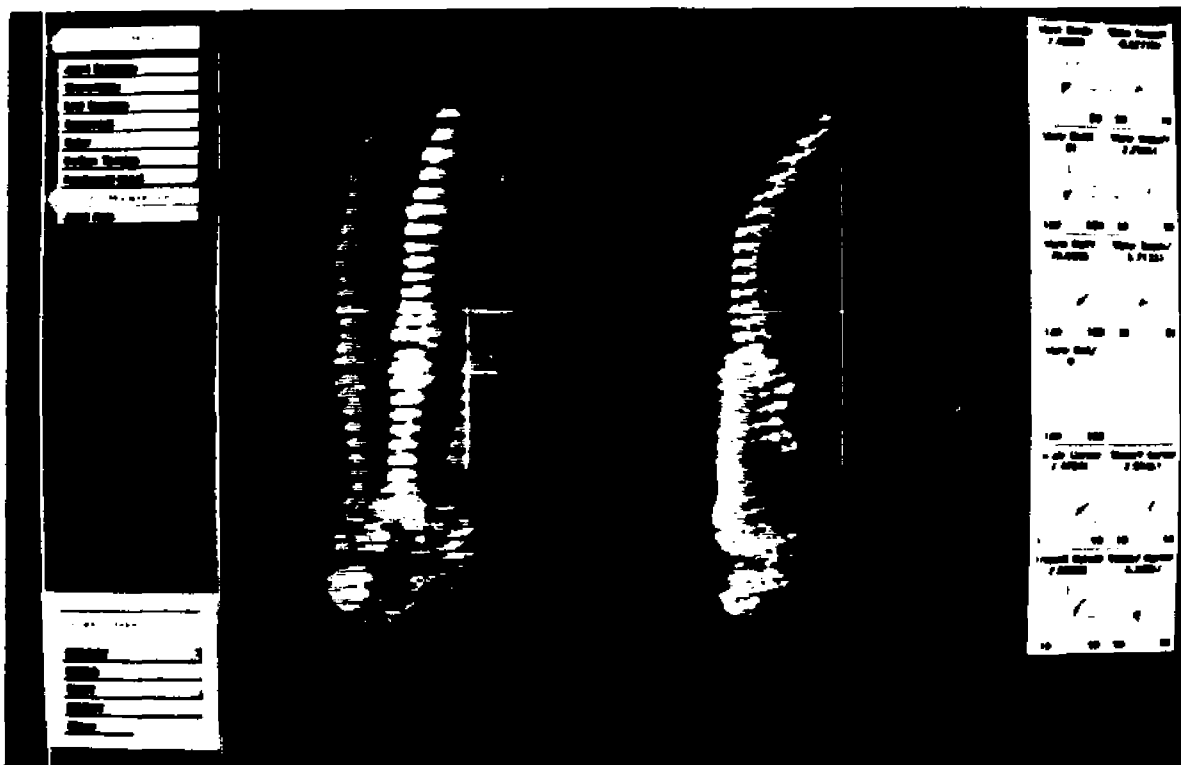


Figure 4.4: Two orthogonal displays of the hand along with two orthogonal cursors.



Figure 4.5: The procedure of picking up the tendon path points.

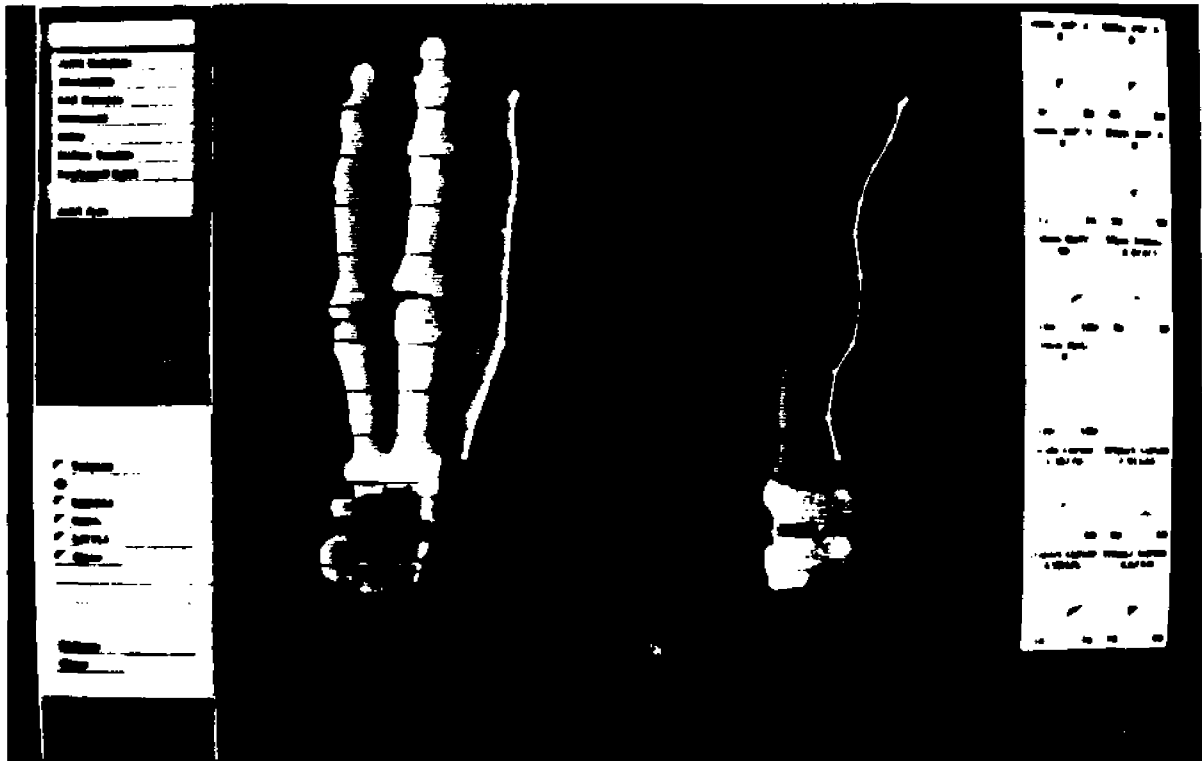


Figure 4.6: The initial tendon path that is the path for the finger in resting position.

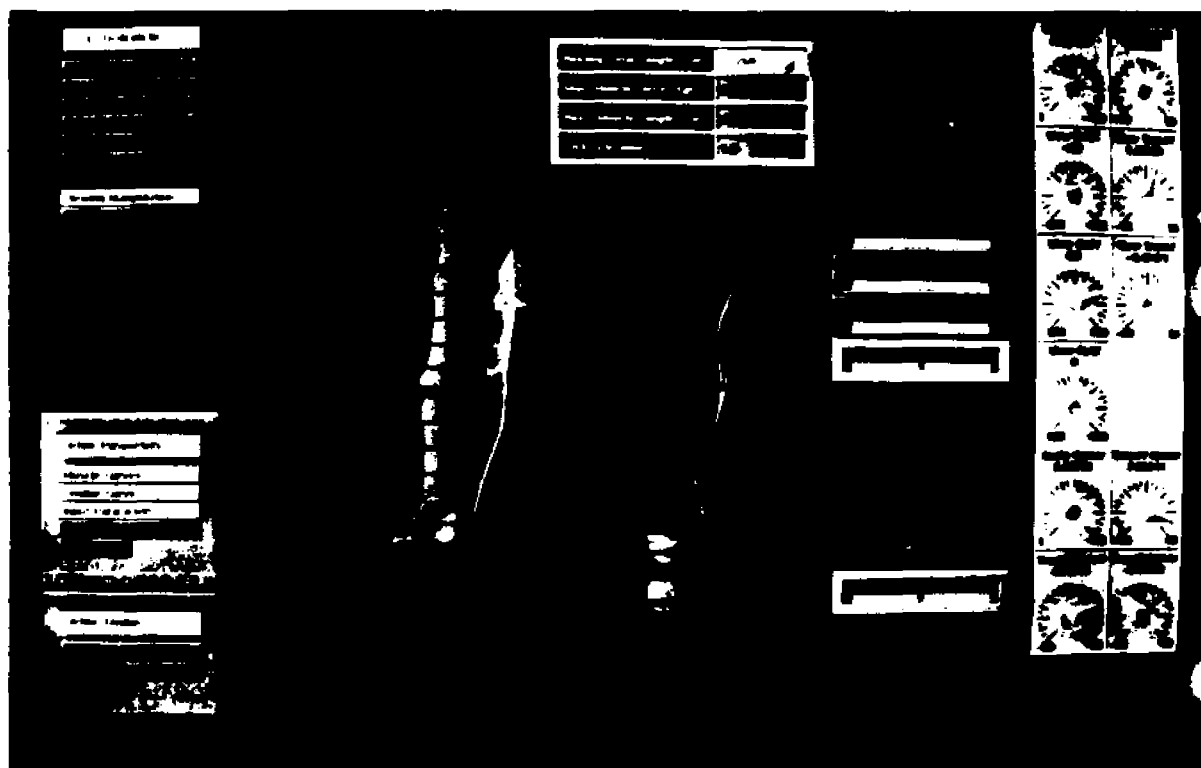


Figure 4.7: Several tendon paths as a result of joint rotation.

4.2 Results

In order to compare the results of the simulation with the experimental data provided by Brand[11], three moment arms for flexion of the Flexor Digitorum Profundus (FDP) were obtained. Those are:

- the moment arm for flexion of the FDP at the metacarpophalangeal (MP) joint of the middle finger with the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints in extension,
- the moment arm for flexion of the FDP at the PIP joint of the middle finger with the MP joint in extension, and
- the moment arm for flexion of the FDP at the DIP joint of the index finger with the MP and PIP joints in extension.

As shown in Figures 4.8 and 4.9, for the moment arm of the FDP at the MP and PIP joints of the middle finger, the experimental data and the simulation results are close. The quantitative accuracy of the simulation model is within 5% of actual tendon data. For the FDP at the DIP joint of the index finger, the model predicts the moment arm 10% of the value derived from the experimental data. In addition, for each case the qualitative behavior is acceptable. The quantitative errors can significantly be reduced by placing the tendon path points based on anatomical data.

No statistical analysis was attempted because the workstation (theoretical) results were being compared to an average of several cadaver hand specimens.

Figure 4.11 shows some other results that were included in the logfile.

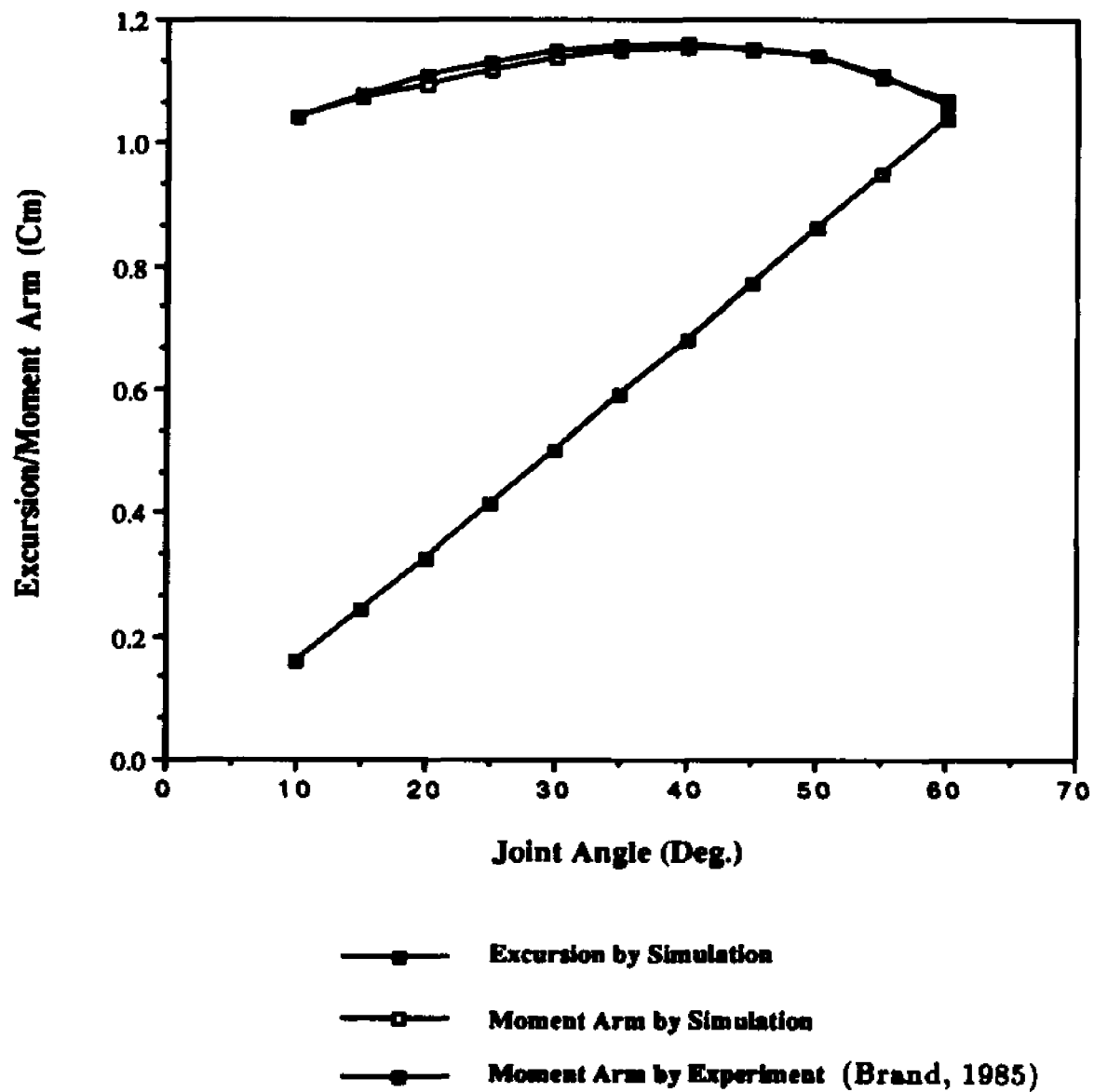


Figure 4.8: The excursion and moment arm for flexion of the FDP at the MP joint of the middle finger with the PIP and DIP joints in extension.

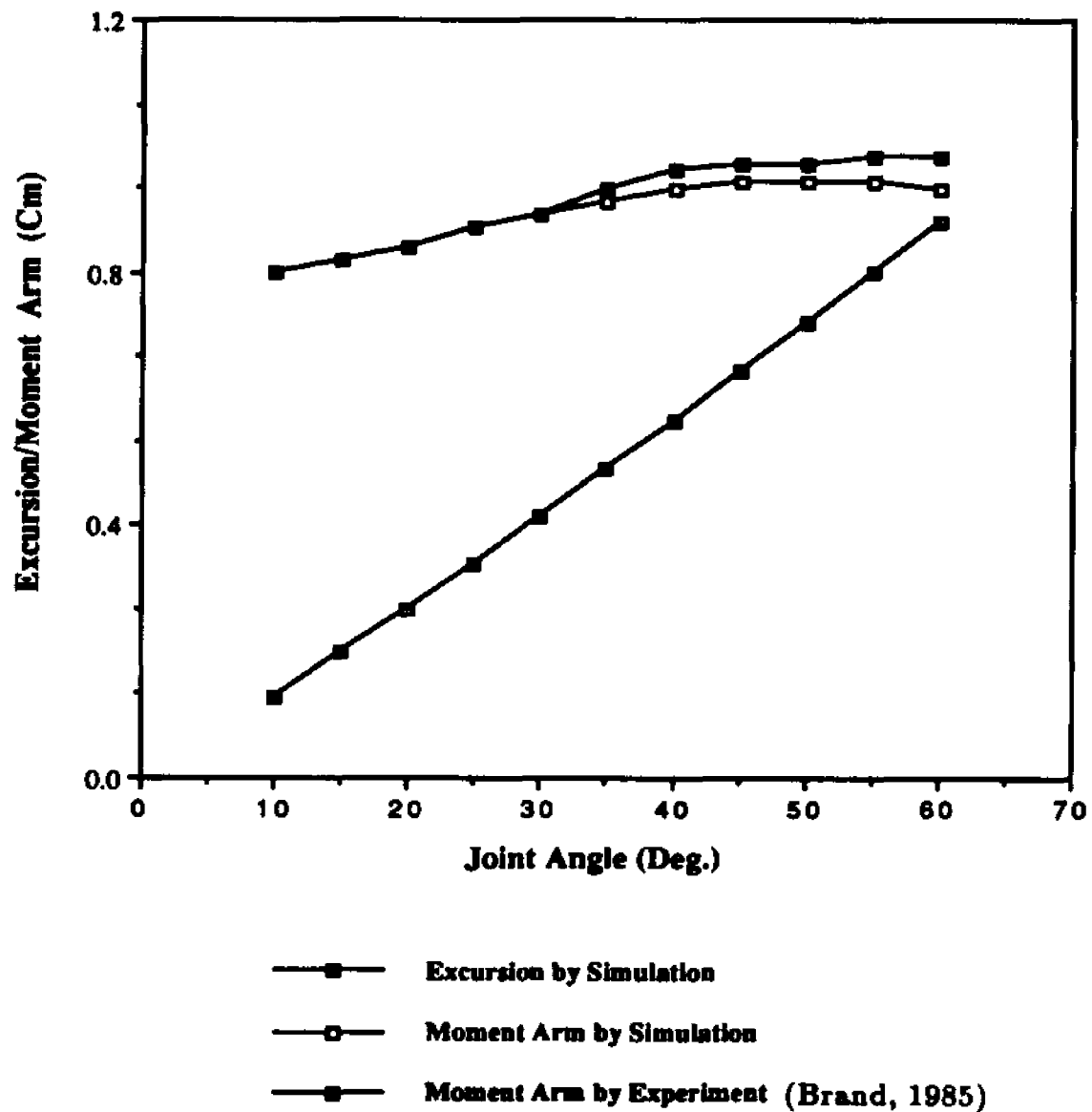


Figure 4.9: The excursion and moment arm for flexion of the FDP at the PIP joint of the middle finger with the MP joint in extension.

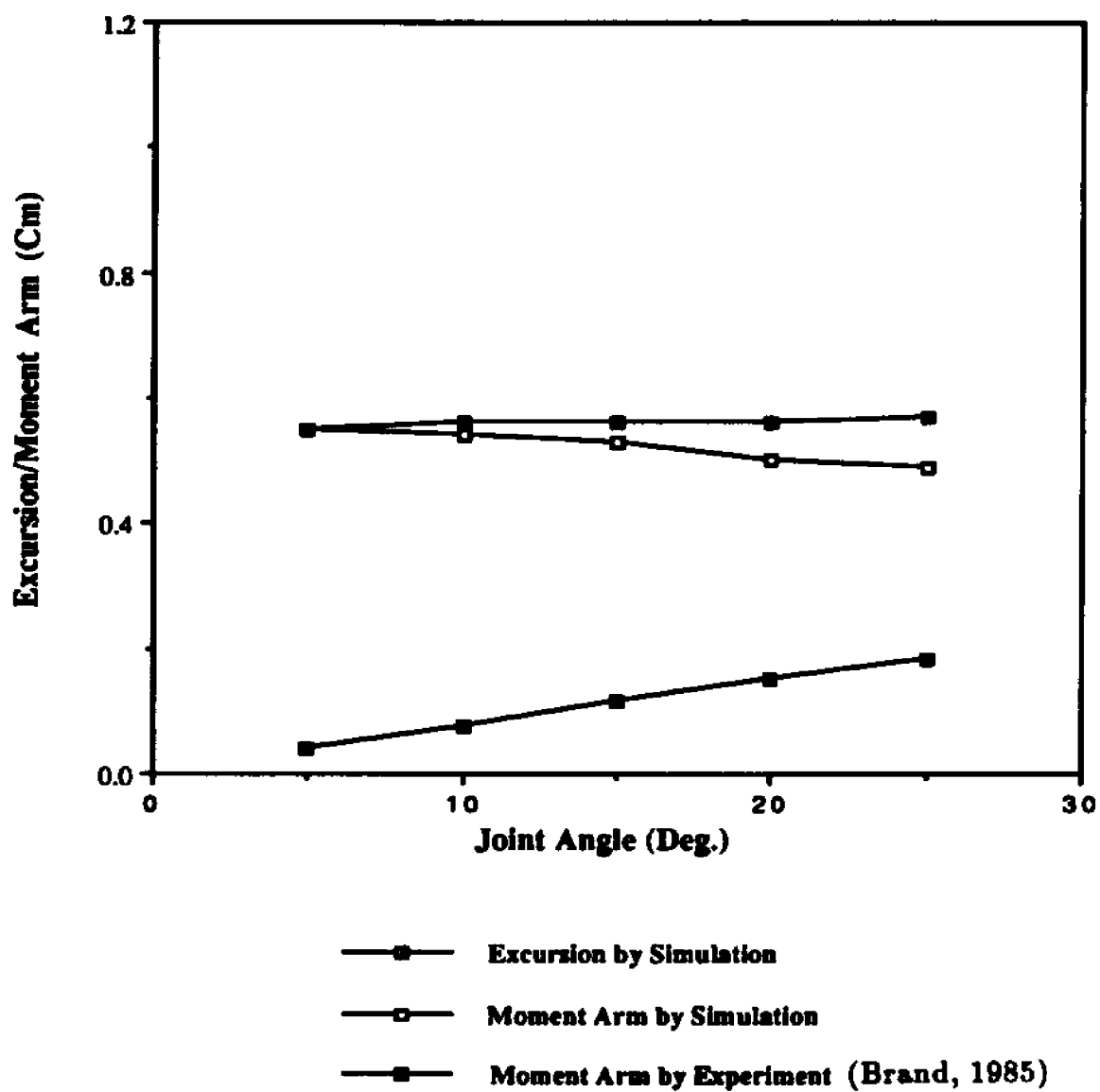


Figure 4.10: The excursion and moment arm for flexion of the FDP at the DIP joint of the index finger with the MP and PIP joints in extension.

/* Simulation Results */

- o Muscle Length in Current Position (L_m) : 3.230 (cm)
- o Tendon Length in Current Position (L_t) : 7.603 (cm)
- o Total Muscle/Tendon Length in Current Position : 10.833 (cm)
- o Normalized Muscle Force (F_m/F_{max}) : 0.852
- o Normalized Tendon Force (F_t/F_{max}) : 0.852
- o Min. Normalized Active Muscle Fiber Length : 0.500
- o Max. Normalized Active Muscle Fiber Length : 1.500
- o Central Nervous System (CNS) Activation: 1.000
- o Max. Normal. Force in Passive Muscle Fiber : 1.000
- o Tendon Strain ((L_t-L_{ot})/ L_{ot}) : 0.046
- o Maximum Force in Muscle : 100.000 (kg)
- o Safety Factor of Tendon : 3.000
- o Intermediate Tendon Strain : 0.050
- o Maximum Tendon Strain : 0.100
- o Muscle Length in Resting Position (L_{om}) : 4.000 (cm)
- o Tendon Length in Resting Position (L_{ot}) : 7.268 (cm)
- o Total Muscle/Tendon Length in Resting Position : 11.268 (cm)

Figure 4.11: The simulation result

Chapter 5

Evaluation Program

In order to test the validity of the use of technology in orthopedic surgery, one must solicit input from the practitioners of this field. This cannot be posed as a single, simple query, rather a set of specific questions from which one can determine whether this technology is appropriate.

The objectives of the evaluation program reported here can be itemized as follows:

1. Measure the usefulness and applicability of the biomechanics workstation concept to the orthopedic community in the three areas of research, education, and clinical care.
2. Determine the strengths and weaknesses of the tendon transfer software, its user interface, the biomechanics methods presented, and other interaction-dependent issues.
3. Establish future directions for research and development efforts.

4. Solicit feedback on the potential for a commercial venture to bring this concept to market. Also obtain information on features needed to make it more acceptable and useful to clinicians.

The procedures for the evaluation program were designed in the following manner:

1. Writing the programs essential to test the hand biomechanics workstation.
2. Inviting orthopedic surgeons who are nationally recognized in the field of hand surgery.
3. Keeping the groups to 2-3 individuals at a time to minimize cross-talk between evaluators, thereby insuring the broadest perspective and analysis of the workstation.
4. Providing an orientation lecture on the methods used and the procedures (tests) which were to be completed by each subject at the workstation console.
5. Immediately after their console session, each subject was asked to complete a written free-form commentary covering the objectives of the study and their personal experiences and feelings. This was guided by a formal questionnaire which is included in Appendix A.
6. At the end of the day, there was a meeting of all reviewers and the staff of the project to discuss the merits and failings of the program. This was

audiotaped to capture the detail of the discussions. These comments have been condensed and are summarized in Appendix B.

7. Analyzing and quantifying the results of this evaluation.

All testing was completed during the November-December 1991 period. The following is a summary of the eight reviewers' critiques on the hand biomechanics workstation for several categories. For clarity, the reviewers' own comments are *italicized*.

- **User Interface**

- *The user interface must get a great deal of attention before it is acceptable to average surgeons.*
- *Need to incorporate CT or MRI data to aid in 3D path selection.*
- *Output data must also be graphically visualized.*
- *Need to be faster.*

- **Commercial Marketability**

- *Not useful in present form on a daily and clinical basis, especially if it's expensive.*
- *If the user interface were refined, it would be immediately useful.*

- **Concept of Forces and Torques**

- *During the evaluation session, the concept was not clear. However, it is extremely important as basis for hand reconstruction. (Note: 50% of reviewers felt that it was unclear so that we obviously needs a better means of portrayal. This was challenging for a 60 min. program which our surgeons were subject to. Time spent of force, torque was just a small portion of this hour.)*

- **Screen Size and Resolution Adequacy**

- *the screen size and resolution of the workstation were excellent.*

- **Usefulness of the concept of a hand biomechanics workstation for clinical application**

- *Very important: 4, Somewhat important: 3, Not important: 1*

- **Usefulness of the concept of a hand biomechanics workstation for educational application**

- *Very important: 7, Somewhat important: 1, Not important: 0*

- Usefulness of the concept of a hand biomechanics workstation for research application

– *Very important: 7, Somewhat important: 1, Not important: 0*

- How do you rank the importance of those three applications?

Rank	1	2	3	Scaled Total
<i>Research Application</i>	4	4	0	20
<i>Educational Application</i>	4	3	1	19
<i>Clinical Application</i>	0	1	7	9

(Note: As described in the above table, the reviewers considered that the hand biomechanics workstation would be the most useful in the research application with the educational application considered the next. Because of its incompleteness, it was considered the least applicable to the clinical care.)

Chapter 6

Conclusions and Future Extensions

6.1 Conclusions

The major contributions of this research are as follows:

1. An interactive graphics based musculotendon modeling for the hand was developed that allows users, primarily hand surgeons, to simulate and manipulate easily the musculotendon model of the hand that are in a normal or pathological state. Since this model uses a current standard graphical library and user interface, it could be transported easily to other systems with minor modification.
2. The tendon path planning model for the hand was developed to permit users to base tendon transfer surgical procedures on *quantitative* methods rather than on *subjective* methods. This model can calculate the origin-to-insertion distance of the musculotendon path, excursion, and forces in muscle and tendon. The mathematical computations from the tendon path

simulation for the hand will, for the first time, permit a surgeon to know what excursion would be required of the muscle in its role.

3. The tendon path planning model for the hand was used to obtain the moment arms of flexion of the Flexor Digitorum Profundus (FDP) of the metacarpophalangeal (MP) and proximal interphalangeal (PIP) joints of the middle finger and the distal interphalangeal (DIP) joint of the index finger and to compare its results with the experimental data.

As stated in Chapter 1, the hypothesis of this dissertation was that a hand biomechanics workstation would be useful and applicable to the field of orthopedic surgery of the hand. One of the objectives of this research was to test this hypothesis, that is, to determine the *validity* of the workstation for the three areas of *research, education, and clinical applications*. To this objective, an interactive computer graphics based musculotendon modeling of the hand was developed and combined with other software for evaluation by the orthopedic surgeons of varying backgrounds.

Those other software tested by the reviewers along with this work are:

- 3D visualization of soft tissues using the AVS (Application Visualization System) by Myers,
- External force and torque analysis by Giurintano[21], and
- Bone surface modeling for visualization using AVS by Odesanya[30].

During the evaluation session all of the reviewers felt that the purposes of the evaluation program of the hand biomechanics workstation were clear enough to be understood. The present user interface, however, seemed somewhat uncomfortable to them. Even though the difficulty partially resulted from a very brief orientation on the procedures prior to evaluating the system, the present user interface must be made more user-friendly for the average surgeon, most of whom have been reluctant to experience the world of computers. Considering that the user is supposed to be an *average surgeon*, not a *computer specialist*, the user interface plays a major role in the hand biomechanics workstation.

Although the workstation is very incomplete in its present form, the orthopedic surgeons in the evaluation program felt that interactive graphics based musculotendon modeling for the hand has usefulness and applications for research, education, and clinical practice. The consensus was that the workstation was most applicable to research and education initially but that clinical applications would eventually be possible.

In addition to its usefulness for routine type tendon transfers, this software can also be useful for clinicians in complex tendon transfers such as multiple nerve injuries and brain-injured hand pathologies that are not routinely carried out, since these complicated pathological situations can be visualized and simulated on the system in three dimension. This was felt by many to be one of the main advantages of using a computer simulation model prior to the actual surgical

procedure on a patient's hand. The comparison of the actual data from pre- and post- operation tests can demonstrate the value of the workstation as a useful tool in predicting the possible outcome of a given operation.

With the concept of forces and torques at the various joints, the software can simulate the prothesis design of the hand, such as designing axes and determining forces and torques across the joints which are very critical in the prothesis design. As a tool for analyzing the prototype prothesis, employing the concept of the finite element analysis can be an excellent idea.

For the visualization of the anatomical structure, this software is limited to bones and partially tendons. Extending the three dimensional visualization to the other anatomical structures, such as soft tissues, vessels, ligaments, and nerves, would be extremely helpful in the field of education for medical students as well as patients.

In particular, since most of three dimensional medical images of the human body are mainly based on CT scans that are very effective to represent bones and MR images that are also effective for soft tissues, superimposing MR images on top of CT scans can have a great deal of potential in the educational and research applications. Employing the stereo image technique, however, requires a significant amount of work into the visualization of anatomical structures. This is not considered adequate at this stage, because 3D visualization without stereo images can deliver acceptable images for diagnostic and planning purposes.

6.2 Future Extensions

The possible future extensions for this research are listed as follows in the order of priority and time required:

Improving user interface: Since the end user will be an average surgeon who is not computer-oriented, it is imperative that the user interface needs to be much more user-friendly. Specifically, using the picking utility in PHIGS would seem to be a great idea to improve user-friendliness. When many primitives displayed on the screen need to be manipulated, using virtual dials might cause delays in the computers' response. When selecting points that define a tendon path, the use of the picking utility will greatly improve user-friendliness. The software additions can be done easily within a short period of time. As one of the reviewers, Dr. Tom Wright, suggested, when the pathological situation is under consideration, it would be helpful if the user can split the screen and display the normal situation in one window so that the user does not need to remember what the normal situation is.

External force and torque analyses: To make this software more valuable and applicable to the surgeon, it is required that the external force and torque analyses[21] be implemented because the concept of the reaction forces at various joints and the torques on the particular bones is critical in prothesis design. In fact, this short-term extension will be complete in the very near future.

Solid modeling: This software used a wire-frame model for the hand to minimize the computer execution time to manipulate the image. Since the solid modeling requires much more mathematical calculation than the wire-frame model does, moving a complex object represented using a solid model is extremely slow, even on the high speed hardware like Stardent GS1000 that was used for this research. Even though its slow response is a serious impediment, solid modeling must be implemented for the final visualization of the hand. In other words, the wire-frame with back face culling and solid modeling for the hand can be invoked at any time so that the intermediate steps in the simulation can be done with the wire-frame model. Since the solid model of the hand has been developed by using AVS (Application Visualization System)[30], applying the AVS solid model of the hand to this research in which PHIGS is a main graphic library is not a difficult task. As Dr. Larry Chidgey stated during the evaluation program, the single line representation of muscles is somewhat confusing and muscles need to be represented as volumes. The volumetric representation of muscles, however, is accompanied with the problem of determining how the muscles change as joints are rotated[18].

Extending to whole upper limb: As most surgeon reviewers suggested, this research needs to be extended to the whole upper limb for its daily basis use. Once this research for the *hand* biomechanics workstation reaches the level where this system can make contributions to the orthopedic surgical community, including

the wrist and lower and upper arms to the system can be done with little extra research because of their kinematic simplicity compared with the hand.

Neurological model based on CMAC: Applying the adaptive control algorithm based on CMAC (Cerebellar Model Articulation Controller) to this research is a long-term project in our laboratory, the IMRLAB (Interactive Modeling Research Laboratory). As a beginning task, indeed, the concept of CMAC has already been applied to the index finger that was modeled as a 6-link manipulator[27]. This long-term project has great deal of potential in the design of a dexterous robotic manipulator that functions like a human hand.

Bibliography

- [1] *PS300 User's Manual*. Evans & Sutherland.
- [2] *Stellar Graphics Interfaces / Programmer's Guide*. Stardent Computer Inc.
- [3] SS Abi-Ezzi and AJ Bunshaft. An implementer's view of phigs. *IEEE Computer Graphics & Applications*, 12-23, 1986.
- [4] KN An, EY Chao, WP Cooney, and RL Linscheid. Forces in the normal and abnormal hand. *J. Orthopaedic Research*, 3:202-211, 1985.
- [5] KN An, EY Chao, WP Cooney, and RL Linscheid. Normative model of the human hand for biomechanical analysis. *J. Biomechanics*, 12:775-788, 1979.
- [6] KN An, WP Cooney, EY Chao, LJ Askew, and JR Daube. Determination of forces in extensor pollicis longus and flexor pollicis longus of the thumb. *J. Appl. Physiology*, 54(3).
- [7] KN An, K Takahashi, TP Harrigan, and EY Chao. Determination of muscle orientations and moment arms. *J. Biomechanical Engineering*, 106:280-282, 1984.
- [8] RW Baidon and AE Chapman. A new approach to the human muscle model. *J. Biomechanics*, 16(10):803-809, 1983.
- [9] N Berme. Forces transmitted by the finger and thumb joints. *Acta Orthopaedica Belgica*, 46:669-677, 1980.
- [10] PW Brand. Biomechanics of tendon transfer. *Orthopedic Clinics of North America*, 5(2):205-230, 1974.
- [11] PW Brand. *Clinical Mechanics of the Hand*. The C.V. Mosby Company, St. Louis, Missouri, 1985.
- [12] PW Brand, KC Cranor, and JC Ellis. Tendon and pulleys at the metacarpophalangeal joint of a finger. *J. Bone and Joint Surgery*, 57(6):779-784, 1975.

- [13] HJ Buchner, MJ Hines, and H Hemami. A dynamic model for finger interphalangeal coordination. *J. Biomechanics*, 21:459–468, 1988.
- [14] WL Buford. *Interactive Three Dimensional Computer Graphics Simulation of the Kinematics of the Human Thumb*. PhD thesis, Louisiana State University, December 1984.
- [15] WL Buford and DE Thompson. A system for three-dimensional interactive simulation of hand biomechanics. *IEEE Transactions on Biomedical Engineering*, BME-34(6), 1987.
- [16] EY Chao, JD Opgrande, and FE Axmear. Three dimensional force analysis of finger joints in selected isometric hand function. *J. Biomechanics*, 19(6):387–396, 1976.
- [17] WP Cooney and EY Chao. Biomechanical analysis of static forces in the thumb during hand function. *J. Bone and Joint Surgery*, 59(1):27–36, 1977.
- [18] SL Delp. *Surgery Simulation: A Computer Graphics System To Analyze and Design Musculoskeletal Reconstructions of the Lower Limb*. PhD thesis, Stanford University, August 1990.
- [19] SL Delp, JP Loan, MG Hoy, FE Zajac, EL Topp, and Rosen JM. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. *IEEE Transactions on Biomedical Engineering*, 37(8):757–767, 1990.
- [20] JR Doyle and WF Blythe. Anatomy of the flexor tendon sheath and pulleys of the thumb. *J. Hand Surgery*, 2(2):149–151, 1977.
- [21] DJ Giurintano and A Hollister. Force analysis of the thumb for a five-link system. *1991 Biomechanics Symposium, ASME*, 1991.
- [22] DJ Giurintano and DE Thompson. A flexor tendon model of the hand. *Automedica*, 11:53–70, 1989.
- [23] H Hatze. The complete optimization of a human motion. *Mathematical Biosciences*, 28:99–135, 1976.
- [24] WH Hollinshead. *Textbook of Anatomy*. Harper & Row, Philadelphia, 1974.
- [25] MG Hoy, FE Zajac, and ME Gordon. A musculoskeletal model of the human lower extremity: the effect of muscle, tendon, and moment arm on the moment-angle relationship of musculotendon actuators at the hip, knee, and ankle. *J. Biomechanics*, 16(6):419–425, 1983.

- [26] O Jones. *Introduction to the X Window System*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1989.
- [27] S Kwon. *An Adaptive Control System for Biological Simulations*. PhD thesis, Louisiana State University, December 1990.
- [28] JMF Landsmeer. Studies in the anatomy of articulation. *Acta. Morphol. Neerlandico-Scandinavia*, 3:287-321, 1961.
- [29] LM Myers, WL Buford, DJ Giurintano, and DE Thompson. Interactive segmentation of three-dimensional anatomical data for musculoskeletal modeling. NCGA 88 Conference, Anaheim, CA, March 20-24 1987.
- [30] OS Odesanya. *Construction of Biological Surface Models from Cross-Sections*. Master's thesis, Louisiana State University, December 1991.
- [31] CJ Ou. *The Biomechanics of the Carpometacarpal Joint of the Thumb*. PhD thesis, Louisiana State University, December 1979.
- [32] D Shuey, D Bailey, and TP Morrissey. Phigs: a standard, dynamic, interactive graphics interface. *IEEE Computer Graphics & Applications*, 50-57, 1986.
- [33] BR Thatch and A Myklebust. A phigs-based graphics input interface for spatial-mechanism design. *IEEE Computer Graphics & Applications*, 26-38, 1988.
- [34] DE Thompson, WL Buford, LM Myers, DJ Giurintano, and JA Brewer. A hand biomechanics workstation. In *Proc. ACM Computer Graphics*, pages 327-334, 1989.
- [35] DE Thompson and DJ Giurintano. A kinematic model of the flexor tendons of the hand. *J. Biomechanics*, 22:327-334, 1989.
- [36] I Yoon and DE Thompson. An interactive graphics based tendon path planning method. *Advances in Bioengineering*, 8, 1988.
- [37] I Yoon and DE Thompson. Planning tendon paths using an interactive graphic workstation. *J. of Biomechanical Engineering*, 112, 1990.
- [38] FE Zajac. Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. *Critical Reviews in Biomedical Engineering*, 17:359-411, 1989.

Appendix A

This is a list of the questionnaire that was asked to the orthopedic surgeon reviewers. The individual audio tapes of the responses of each reviewer to each question posed were reviewed and summarized.

EVALUATION PROGRAM Hand Biomechanics Workstation

Name:

Date:

At this time, you have been able to spend a minimum of one hour at the controls of the research prototype of a hand biomechanics workstation and have seen our ideas for its present and future applications. The following are specific questions related to the work you have reviewed that we would like your input on. Please feel free to expand on any issue you think needs more emphasis. The very last question has been placed there for you to spend as much time on as you wish and to offer free-form, unstructured commentary.

1. Do you feel that the purposes of the proposed workstation were made sufficiently clear to you?
2. Is the present user interface acceptable? Please elaborate on what you found to be too tedious or unnatural or altogether useless. Specifically comment on the relative usefulness of the various methods provided by which you could manipulate the view of the hand or define tendon paths.
3. What specific new applications should we focus on to expand the application suite for the workstation (eg. prosthesis implantation simulation, bone remodeling tools, demonstration of common surgical procedures, etc.)?
4. Do you feel that there is a commercial market for this type of workstation to be used on a surgeon's desk? If so, within what timeframe and what cost seems reasonable for such a clinical tool?
5. Do you feel that the concept of forces and torques at joints was made clear to you in the presentation or the demonstration? Do you feel that these concepts are important in a clinical environment?
6. Is the 3D visualization of the bony structures of the hand in any way helpful to you as a medical student? As a research tool? As a clinician? Would similar visualization tools for other anatomical structures (eg. soft tissues, tendons, nerves) be useful?
7. Do you feel true stereo images are essential to the success of this endeavor or is the current display of 3D information acceptable?
8. Comment on whether the time required to use the hand biomechanics workstation is an impediment to its function, helpful in that it forces one to study the detail of the procedure involved, or that the time required precludes its use clinically?

9. Was the response of the workstation too slow? If so, was this a major impediment to its use?
10. Was the screen size adequate for the visualization required? Was the resolution acceptable for the proposed purposes?
11. Was the information presented to you in each situation clear enough to allow you to decide what to do next? Were there times when you just felt lost?
12. Do you think the concept of a hand biomechanics workstation for the clinical practice of orthopedic surgery is useful?
13. Do you think the concept of a hand biomechanics workstation for physician education at the residency, fellowship, or CME level is useful?
14. Do you think the concept of a hand biomechanics workstation for research in orthopedic surgery is useful?
15. If you have any other feelings, either positive or negative, please take this opportunity to provide us with your critical feedback.

Appendix B

This appendix includes a summary of review statements.

Reviewer : Tom Wright, M.D.
Assistant Professor
Department of Orthopedics
University of Florida Medical School
Gainesville, Florida 32610

Date : Nov. 25, 1991

1. The purposes of the proposed workstation were clear.
2.
 - For the tendon excursion portion of the program, positioning of points along the tendon is somewhat time-consuming.
 - User interface needs to be made extremely simple, menu-driven, and relatively not very time-consuming because users are not computer experts and will not be using computers on daily basis.
 - Can not comment on specifics.
3.
 - Significant needs for evaluating prothesis and computer simulated model prior to the in-vivo use which is commonly done today.
 - Ligaments need to be represented.
 - Superimposing MR for a soft tissue on top of CT reconstructions for bony resolution would be very helpful.
 - Computer model would be useful in demonstrating certain surgical procedures prior to the actual procedures.
4.
 - Several possible markets.
 - Resident education.
 - Research applications for development of new prothesis.
 - Clinical applications for complex tendon transfer.
 - Clinical situation used for non-routine type tendon transfer.
 - Individual surgeon does not want to invest significant expense or time in using computers.
 - Computer could be very helpful in complex transfers such as multiple nerve injuries and brain-injured hand pathology.
5.
 - The concept of forces and torques at joints was relatively clear during demonstration.
6.
 - 3D visualization is an excellent way of teaching anatomy to medical students and clinicians.
 - It has potential for applications as a research tool.

- Superimposing MR for a soft tissue on top of CT reconstructions for bony resolution would be very helpful.
7. The current display of 3D information is very acceptable.
 8. The hand biomechanics workstation will force one to study the detail of the procedure assuming that one is not directed to the keyboard rather than image itself.
 9. The response of the workstation is slow even though it is not a major impediment.
 10. The screen size and resolution were adequate for the visualization.
 11. Difficult to answer.
 12. The hand biomechanics workstation has some potential, partially in clinical practices that do not deal with routine surgery but deal with more complex problems.
 13. The hand biomechanics workstation is useful for physician education at the residency.
 14. The hand biomechanics workstation is very useful for research, particularly prosthesis design.
 15.
 - The hand biomechanics workstation would be useful in particular complex paralyzed hand.
 - It would be helpful if user can split the screen and put a normal situation in one window so that the user doesn't have to remember what the normal situation is.
 - Rated 1: Research application.
 - Rated 2: Educational application.
 - Rated 3: Clinical application.

Reviewer : Paul Dell, M.D.
Professor and Chairman
Department of Orthopedics
University of Florida Medical School
Gainesville, Florida 32610

Date : Nov. 25, 1991

1. The purposes of the proposed workstation were understood.
2.
 - A great deal of computer knowledge is needed to work this program which would need to be simplified for common users.
 - Ability to manipulate the view of the hand and define tendon path is wonderful.
 - Problem with tendons and their excursion with various joint motions is that it appears to be somewhat arbitrary in placing tendon path points. Distance from the bone to the tendon should be defined anatomically and fed into the data format.
3.
 - New applications could include the localization of tumor.
 - If data base includes normal anatomy of the hand, then the localization of tumor could be defined. - Surgeon would know the plane of dissection of what tissues need to be included in the dissection.
 - Tendon rerouting procedure could be confirmed at the workstation prior to implementation in a patient.
 - If the visualization tools include the relationship of soft tissues, tendons, nerves, and vessels, these could be extended to medical students as well as for every day employment in conferences and discussions.
 - Prosthetic implantation design as well as understanding failure in the prosthesis would be a natural extension.
4.
 - There is a commercial market for this type of workstation.
 - The price range for these programs to be utilized for research and education would be \$20,000-30,000.
 - The price range for these programs to be utilized for practitioners would be \$5,000-7,000.
5. The concept of forces and torques was clear and are important in a clinical environment.
6.
 - The 3D visualization of the bone structures of the hand is useful as a research tool but is not useful to medical students and clinicians.

- If the visualization tools include the relationship of soft tissues, tendons, nerves, and vessels, these could be extended to medical students as well as for every day employment in conferences and discussions.
7. The current display of 3D information would be acceptable without stereo images.
 8. Time requirement for the hand biomenchanics workstation is not an impediment.
 9. The response of the soft tissue simulation was a little slow, but not a major impediment to its use.
 10. The screen size was certainly adequate for the visualization. The resolution was excellent.
 11.
 - Was totally lost - having computer experts run the program was fruitful.
 - Do not know what the next step would be.
 - Simplifying into the type of menu-driven program would be imperative.
 12. The hand biomechanics workstation is important in clinical practice.
 13. The workstation for physician education at the residency and fellowship is useful.
 14. The workstation is the most useful for the field of research.
 15.
 - Impressed with the progress that has been made.
 - It is imperative to have data base which is based on anatomy as the bottom line for tendon transfer program.
 - Rated 1: Educational application.
 - Rated 2: Research application.
 - Rated 3: Clinical application.

Reviewer : Larry K. Chidgey, M.D.
Assistant Professor
Department of Orthopedics
University of Florida Medical School
Gainesville, Florida 32610

Date : Nov. 25, 1991

1. The purposes of the proposed workstation were clear.
2.
 - User interface needs to be made as user-friendly as possible and as little typing as possible.
 - Dynamic components should be in real time.
 - Surgeon should be prompted for each value in a very clear and understandable questions.
3.
 - At this phase the data is general enough in the sense that inputting a specific patient's data would be somewhat difficult.
 - Muscle fiber alignment would be helpful in conceptualizing how the muscle is working.
 - It could be used in prosthetic design for designing axes and balancing forces across joints.
4.
 - For educating a large number of surgeons, \$10,000-12,000 is a reasonable price range.
 - \$5,000 is more reasonable for a software package running on 386 and 486 based PC's or Macintosh.
5. The evaluation of forces and torques at various joints is critical in understanding the reconstruction of the hand.
6.
 - The dynamic 3D visualization of anatomy is important in understanding what's going on in the hand as well as surgical approaches.
 - The way to quantify the values would be very helpful in the research environment with regards to excursions and bone motions.
7. Stereo image is not critical to the current 3D format.
8. The hand biomechanics workstation needs to be made much more user-friendly and as menu-driven as possible with very little thinking.
9. No comments.
10. The screen size and the resolution were adequate.

11. It would take several days to weeks with this software to get the feel of what's going on.
12. It has least potential for clinical practice.
13. The workstation has the biggest potential as an educational tool - needs to be more user-friendly.
14. As a research tool, it can simulate prosthetic designs and generate new prosthetic design.
15.
 - The single line representation of muscles was confused.
 - In force analysis program, some engineering terms such as negative numbers and vector direction were confused.
 - Rated 1: Educational application.
 - Rated 2: Research application.
 - Rated 3: Clinical application.

Reviewer : Anne M. Hollister, M.D.
Assistant Professor
Division of Orthopedic Surgery
University of California, Los Angeles
Harbor UCLA Medical Center
1000 W. Carson Street, Bin 422
Torrance, CA 90509

Date : Dec. 2, 1991

1. The purposes of the proposed workstation were made sufficiently clear.
2.
 - The present user interface is acceptable for engineers and those who are familiar with graphics computers.
 - The user interface as it is would not be acceptable for the average or even above average orthopedic surgeon who is used to much more user-friendly environment with much less complicated tasks.
3.
 - To bring these concepts in an interactive or videotape format to orthopedic surgeons is a very important contribution that this computer makes.
 - The specific applications that should be focused on would include
 - prosthesis implantation simulation - needed in the orthopedic and prosthetic community.
 - bone remodeling tools - the use of computers to work out the reaction forces at the joint level and the moment on the particular bones would be very useful.
 - demonstration of common surgical procedures - the computer can show the results of several common surgical procedures in terms of force analysis.
4.
 - The average surgeons would not be interested in the workstation because they are not adapted using this kind of computer.
 - As the price of computers goes down, the capabilities go up and the workstations become more user-friendly, surgeons will be more interested in this type of a tool, not on their desks but in a teaching situation, during courses, or possibly in the medical library.
5. The concept of forces and torques at joints is extremely important.
6.
 - The 3D visualization of the bony structures of the hand is very helpful to a medical student, a researcher, or a clinician.

- Similar visualization tools are extremely useful for tendons and somewhat useful for nerves and artery.
7. The current display of 3D information would be acceptable.
 8. The time required now is an impediment - By structuring demonstrations that surgeon can go through in a useful way the time required can be greatly decreased and the amount of useful information to the surgeon can be increased.
 9. The response of the workstation is slow and is a major impediment to use.
 10. The screen size and resolution were adequate.
 11. The information presented in each situation was clear enough.
 12.
 - The concept of the hand biomechanics workstation for the clinical practice is useful in tendon transfers and reconstructive surgery.
 - Most surgeons are not clamoring to use graphics workstations.
 13.
 - The concept of the hand biomechanics workstation for physician education is definitely useful, but it takes expert assistance running the program.
 - If state of knowledge is encoded in the workstation, this would enable therapists and surgeons to do proper therapy and treatment.
 14. The concept of the hand biomechanics workstation for research is absolutely useful.
 15.
 - Rated 1: Research application.
 - Rated 2: Educational application.
 - Rated 3: Clinical application.

Reviewer : H. Relton McCarroll, M.D.
Presbyterian Medical Center
2351 Clay Street, Suite 510
San Francisco, CA 94115

Date : Dec. 2, 1991

1. The purposes of the proposed workstation were clear.
2.
 - The present user interface is well under way, but not currently acceptable for every day use.
 - The method of inputting data for the tendon transfer is cumbersome and time consuming for clinical use. - It might be useful in early stages in a solely research oriented project.
 - The location of tendon points should be selected by positioning a mouse pointer and clicking, instead of rotating the dials.
 - Tendon paths should be drawn by simply clicking both beginning and end points.
3.
 - In running the program the user should be able to go back and change something without having to rerun the program.
 - It seems worth pointing out that the wrist may be an easier joint to model.
 - Addition of distal radius and ulna into the present model is worth while trying.
4.
 - In the future there will be some type of a commercial product available that is basically a workstation for surgeons.
 - To be practical getting CT and MRI tapes from radiologists into a office or home computer needs to be easy.
 - The cost range should be \$5,000 or less.
5. The concept of forces and torques at joints was not clear, but it would not be a problem if this workstation is used regularly.
6. The 3D visualization of the bony structures was marvelous.
7.
 - The current 3D information is quite acceptable.
 - True stereo image is interesting to see, but it does not need to be done.
8. If this program becomes quick and easy to use as well as bulletproof, the time spent worrying about some of the engineering details will probably be useful to the surgeon and his patient.

9. The response of the workstation is slow when trying to move the cursor using the virtual dials.
10. The screen size is more than adequate and the resolution is excellent.
11. In running the program the user should be able to go back and change something without having to rerun the program.
12. The workstation for the clinical practice of orthopedic surgeon has tremendous potential.
13.
 - The education potential for the workstation is immense even though there are so many structures to introduce.
 - The anatomical data base on nerves, vessels, and all the other structures can not be ignored.
14.
 - The biomechanics workstation for research purposes is already an excellent idea.
 - On the verge of being acceptable now to individual researchers. - Tendon transfer application is almost there.
 - Worried about sharing of data by radiologists.
 - If the presently available software were finished in bulletproof form and included the algorithm for manipulation of CT and MRI scans, there would be a beginner's market even at the present time.
15.
 - Rated 1: Research application.
 - Rated 2: Clinical application.
 - Rated 3: Educational application.

Reviewer : John M. Agee, M.D., FACS
Hand Biomechanics Laboratory
77 Scripps Drive, Suite 101
Sacramento, CA 95825

Date : Dec. 9, 1991

1. The purposes of the proposed workstation were clearly understood.
2.
 - The current user interface is more than adequate - The interface can be easily used.
 - It would not be of value to clinicians in its current state.
3.
 - If we focus on a functional loss, one can visualize the clinical situations such as imbalance of forces across joints that are secondary to muscle paralysis.
4. For a surgical workstation to be a commercial success, it needs to be designed such that it performs a meaningful work that will support its existence during a period of time in which the hand surgeons and therapists evolve in their appreciation of both the hand biomechanics as well as the value of computer as a tool to help make a clinical decision.
5. The concept of forces and torques at joints was not clear.
6.
 - 3D visualization of normal bony structures and pathological structures is valuable to researchers and clinicians.
 - Once the soft tissues such as ligaments, tendons, nerves, and so on are added to the 3D visualization tool, it would be a powerful tool available for evaluation of the hand as well as for helping medical students.
7. The current 3D information is more than adequate.
8.
 - Currently time is not an impediment to its value as a research tool.
 - For a clinical tool time required would be a serious problem.
9. The response of the workstation is not a impediment for a research tool but would become a major issue as one uses it to solve more complex problems.
10. The screen size and the resolution are not currently major issues.
11. The information presented is clear enough.

12. The concept of a hand biomechanics workstation for using clinical practice is valuable only if it deals with broad scope of clinical data and its biomechanical significance.
13. It is extremely useful in education at the residency.
14. Its value will depend upon its ability to focus on specific clinical entities as well as overall biomechanical concepts in the balance of joints.
15.
 - Rated 1: Educational application.
 - Rated 2: Research application.
 - Rated 3: Clinical application.

Reviewer : Robert Chase, M.D., FACS
Professor
Department of Surgery
Stanford University School of Medicine
Stanford, CA 94305

Date : Dec. 9, 1991

1. The purposes of the proposed workstation were clear.
2.
 - The present user interface is acceptable.
 - Keyboard is a universal user interface for physicians and surgeons. Nevertheless, the interface should be icon-based using mouse interaction technology.
 - With further refinement, it will be much easier to define tendon paths and to acquire from the system data that is useful to clinician who might be planning various tendon transfers and substitutions to overcome variety of deficiencies.
3.
 - While one might wish to think about new applications to expand usefulness of the workstation, the first order business will be to complete the work necessary to make the system useful in the general field of tendon transfer rerouting.
 - It would be a wonderful tool to use in learning anatomical relationships and biomechanical principles in normal hand function.
 - Anxious to use this tool to design new transfers within the upper limb.
 - Computer modeling is very helpful in the design of a new implantable prosthesis for the hand - This is already proven to be true in implants for joints.
4.
 - There is a commercial market for the workstation once it reaches the level where it is user-friendly enough so that a person with the level of computer illiteracy could use it effectively.
 - For time frame such device, once refined, would be useful almost immediately.
5.
 - The concept of forces and torques at joints was quite clear and adequately explained.
 - Until now, most surgeons have approached all of these in a fairly primitive way.
6.
 - 3D visualization of the bony structure is dazzling and particularly intriguing.

- The demonstration showed quite clearly how the enormous data base which has been collected may be used effectively to visualize the structures in terms of relationships, potential range of motion, and so on.
 - It would be an excellent research tool and learning resource.
7. Not sure how much this stereo image contributes to usefulness but it certainly would be one more element of reality to the system.
 8. The time required to use the hand biomechanics workstation is not an impediment to its function for most of surgeons.
 9. The response speed of the workstation is largely attributable to users, not the system itself.
 10. The screen size was adequate to visualize necessary materials and the resolution was remarkably good.
 11. The information presented is clear enough.
 12. The workstation for clinical practice would be useful but busy orthopedic surgeons may not be willing to take time necessary to make proper use of the system as useful as it might be.
 13. The major usefulness of the system would be a part of every educational program.
 14. The hand biomechanical workstation would be useful as a research tool, particularly in the design of new surgical prosthesis.
 15.
 - In summary, very enthusiastic about the prospect of a future hand biomechanical workstation.
 - very positive in support of its continuing development.
 - Rated 1: Educational application.
 - Rated 2: Research application.
 - Rated 3: Clinical application.

Reviewer : Robert Szabo, M.D.
Department of Orthopedic Surgery
University of California School of Medicine
2230 Stockton Blvd.
Sacramento, CA 95817

Date : Dec. 12, 1991

1. The purposes of the proposed workstation were made clear.
2.
 - The present user interface is acceptable to a very limited group of people.
 - The visual effects are very good, however, the ability to manipulate the data is in fact very tedious and unnatural.
 - The output data needs to be visually presented using graphs.
3. The whole upper extremity could be mathematically modeled.
4. The average clinician would not be willing to spend time nor money to figure out what is the best for his individual patient.
5.
 - The concept of forces and torques at joints was not clear in the presentation.
 - These concepts are very important in a clinical environment.
6.
 - The 3D visualization of the bony structures of the hand is very helpful to medical students, researchers, and clinicians.
 - Similar visualization tools for other anatomical structures, in particular, ligaments and nerves would be very helpful.
7. True stereo images are not essential.
8.
 - The time requirement to use the hand biomechanics workstation precludes its use clinically.
 - The present form of the hand biomechanics workstation is not in the most user friendly mode desirable.
9. The response of the workstation was not a major impediment to use.
10. The screen size was adequate and the resolution was acceptable for the proposed purposes.
11. The information presented was not clear enough.

12. The concept of the hand biomechanics workstation for clinical practice would not pan out.
13. The concept of the hand biomechanics workstation for physician education, once perfected, will be extremely useful, particularly at the hand fellowship level.
14.
 - The concept of the hand biomechanics workstation for research is useful.
 - The present interface requires a commitment to computer and time.
15.
 - Its greatest application will be in academic centers where teams of physicians and engineers can work together in research environment.
 - This project is in embryonic stages.
 - Rated 1: Research application.
 - Rated 2: Educational application.
 - Rated 3: Clinical application.

Vita

Inmo Yoon was born on August 14, 1958 in Chonan, Korea. In 1976, he was graduated from Kyung Bok High School in Seoul. He received a B.S. from Han Yang University in 1981 and a Masters of Science in mechanical engineering from Louisiana State University in 1988. At present he is completing the requirements for a Doctor of Philosophy in mechanical engineering.

He is married to Eunsun Yoo and has one child, Suh Young.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Inmo Yoon

Major Field: Mechanical Engineering

Title of Dissertation: Interactive Graphics Based Musculotendon
Modeling For Reconstructive Surgery of the Hand

Approved:

David E. Thompson
Major Professor and Chairman

David Fogel
Dean of the Graduate School

EXAMINING COMMITTEE:

J. Bush Jones
L. Mann

Wm. D. Catalano
M. Sahasrabudhe
Warren Woggon

Date of Examination:

March 9, 1992